Monday Morning, October 2, 2000

Semiconductors Room 306 - Session SC1+EL+SS-MoM

Chemistry of Silicon Oxides and Nitrides Moderator: E. Cartier, IBM

8:20am SC1+EL+SS-MoM1 Atomic-Order Thermal Nitridation of Si(100) and Subsequent Epitaxial Growth of Si, *T. Watanabe*, *M. Sakuraba*, *T. Matsuura*, *J. Murota*, Tohoku University, Japan

Atomic-order nitridation by NH@sub 3@ on Si(100) and subsequent Si growth by SiH@sub 4@ were investigated using an ultraclean low-pressure CVD system with a Xe flash lamp. Thermal nitridation on Si(100) at 400°C in an NH@sub 3@ environment with and without the flash lamp light irradiation is explained by Langmuir-type physical adsorption of NH@sub 3@ and nitridation by the adsorbed NH@sub 3@. The nitridation can be enhanced by Xe flash lamp light irradiation, and the N atom concentration tends to saturate to about 2.7x10@super 15@ cm@super -2@. In the Si deposition on the ultrathin silicon nitride, it is found that N desorption from the Si nitride films hardly occurs, and Si grew on silicon nitride, whose N atom concentrations are from about 2x10@super 14@ cm@super -2@ to about 2.7x10@super 15@ cm@super -2@, at 385°C in an SiH@sub 4@ environment with and without the flash lamp light irradiation. The incubation period of Si growth is observed and increases with increasing N atom concentration of the silicon nitride film. On the silicon nitride of N atom concentration of about 2x10@super 14@ cm@super -2@, the incubation period is hardly observed and it is found by RHEED measurements that Si epitaxially grew. Layer-by-layer growth control of silicon nitride is proposed by combining atomic-order nitridation on Si and atomic-layer growth of Si on the silicon nitride.

8:40am SC1+EL+SS-MoM2 The Role of Inter-dimer Interactions in NH@sub 3@ Dissociation on Si(100) - (2 x 1), K.T. Queeney, Smith College; K. Raghavachari, Y.J. Chabal, Bell Laboratories, Lucent Technologies

The chemistry of gas-phase precursors to film growth on the Si(100) surface in ultrahigh vacuum is often well-described by localized interaction of the adsorbate with a single Si-Si dimer.@footnote 1@ However, our combined experimental and theoretical studies of the dissociation of NH@sub 3@ to form NH@sub 2@-Si-Si-H on this surface reveal that this reaction is in fact governed by a complex set of inter-dimer interactions involving both bare and adsorbate-covered Si dimers. External transmission FTIR spectroscopy allows us to probe both the lower-frequency @delta@(NH@sub 3@) modes of metastable, undissociated NH@sub 3@ and the higher-frequency @nu@(SiH) modes resulting from dissociation. By comparing our experimental results with density functional calculations describing two-dimer clusters, we find that the vibrational spectra can only be interpreted when inter-dimer effects are considered. Specifically, while hydrogen bonding between undissociated NH@sub 3@ and dissociated NH@sub 2@ species renders coupling of adjacent nitrogen-containing groups thermodynamically favorable, kinetic control of the dissociation process yields a predominance of the opposite configuration, resulting from the influence of dissociated species on the buckling of neighboring bare dimers during adsorption. We propose that such adsorbate-induced effects on the electronic structure of neighboring dimers may have general implications for controlling the two-dimensional ordering of reactions on the dimerized Si(100) surface. @FootnoteText@ @footnote 1@ See for example: R. Konecny and D. J. Doren, J. Chem. Phys. 1997, 106 (2426); B. B. Stefanov and K. Raghavachari, App. Phys. Lett. 1998, 73 (824).

9:00am SC1+EL+SS-MoM3 Quantum Chemical Study of Silicon Nitride Deposition Using Ammonia, Y. Widjaja, C.B. Musgrave, Stanford University Density functional theory is used to examine the reaction mechanisms of nitridation of the Si(100)-2x1 surface by NH@sub 3@. The surface is modeled using the cluster approximation. A detailed reaction mechanism is investigated including ammonia adsorption and decomposition, insertion of N into Si-Si bonds, and H@sub 2@ desorption. We find that nitrogen prefers to be in the subsurface layer, bonded to three Si atoms. The energy barriers leading to the nitridation of the Si(100) surface are also calculated. The activation barrier of the rate limiting step is found to be higher than the activation barrier for NH@sub 3@ desorption. This confirms the experimental observation that a large fraction of the NH@sub 3@ that dissociates on adsorption will recombine and desorb. Furthermore, we have also calculated the vibrational frequencies of various surface nitride structures. The computed frequencies are then compared with the experimental HREELS spectra. The comparison further allows the

unambiguous characterization of the surface species. Using the calculated barriers and frequencies we use transition state theory to estimate a rate for nitridation of the (100) silicon surface. We investigate the validity of the cluster approximation and find that bigger cluster models are necessary to describe the nonlocal electronic effects.

9:20am SC1+EL+SS-MoM4 Thermal Nitridation of Ultrathin Silicon Dioxide Films Using NH@sub 3@ Gas, O. Jintsugawa, M. Sakuraba, T. Matsuura, J. Murota, Tohoku University, Japan

Nitrided ultrathin SiO@sub 2@ film is attractive as the gate insulator of future MOS devices. In this work, thermal nitridation of thin SiO@sub 2@ films and transport of nitrogen species into SiO@sub 2@ films were investigated. A 30Å-thick SiO@sub 2@ film on Si(100) was formed by wet oxidation at 700°C , and was thermally nitrided for 90min at 750-850°C in NH@sub 3@ gas at 100Pa using an ultraclean low-pressure CVD system. The depth profile of N atom was obtained by the repetition of etching by a 1%-diluted HF solution and XPS measurements. By the thermal nitridation. most of the N atoms were present near the SiO@sub 2@ surface and the N atom concentration was remarkably lower (1/2 and 1/10 at 850 and 750°C, respectively) than that of the nitrided Si surface without the SiO@sub 2@ film. By 850°C nitridation. N atom diffused into the SiO@sub 2@ film and Si substrate nitridation were observed. The N atom concentration was estimated to be 4x 10@super 15@cm@super -2@ on the SiO@sub 2@ surface, 1x10@super 21@cm@super -3@ in the SiO@sub 2@ film, and 8x10@super 13@cm@super -2@ at the SiO@sub 2@/Si interface. Binding energy of N 1s at the SiO@sub 2@ surface and in the SiO@sub 2@ film was shifted 2eV-higher than that at the SiO@sub 2@/Si interface. By 750°C nitridation, the N atom concentration on the SiO@sub 2@ surface was 3x10@super 14@ cm@super -2@ and, in the SiO@sub 2@ film and at the SiO@sub 2@/Si interface, the N atom concentration was less than the detection limit (about 3x10@super 20@cm@super -3@ and 4x10@super 12@cm@super -2@, respectively). This result indicates that the existence of surface oxygen more greatly suppresses the reaction of NH@sub 3@ at the lower temperature. Pressure and time dependence of nitridation on the SiO@sub 2@ surface, in the SiO@sub 2@ and at the SiO@sub 2@/Si interface will be also presented.

9:40am SC1+EL+SS-MoM5 Probing the Chemistry of Dielectric Thin Film Growth on Si Surfaces, L.D. Flores, J.E. Crowell, University of California, San Diego INVITED

The surface and gas phase chemistry involved during dielectric thin film growth of doped and undoped silicon dioxide has been studied using the atmospheric pressure reaction between tetraethoxysilane (TEOS) and ozone. The studies involve low temperature deposition of dielectric thin films using a new atmospheric-pressure chemical vapor deposition (APCVD) reactor utilizing a commercial injector / vent assembly. The APCVD reactor is coupled to a N@sub 2@-purged glovebox and a UHV surface analysis facility equipped with XPS, AES, TPD, and IR spectroscopy capabilities. Gasphase transmission FTIR spectroscopy measurements were performed insitu during deposition at 400°C by probing the variable gap region between the 400°C heated Si wafer and the injector. The primary products produced upon reaction of TEOS and ozone are acetic acid, formic acid, formaldehyde, carbon monoxide, carbon dioxide, and water. Reaction of TEOS and oxygen in the gas phase is negligible compared to reactions involving ozone at identical temperatures under these conditions. Potential TEOS / O@sub 3@ reaction products and their reaction with boron and phosphorus containing dopant sources has been investigated in order to clarify their role in the oxidation process and to clarify the chemical mechanism. This was accomplished by following the reaction with ozone of some possible and observed ozonation products in a flow reactor / gas cell using transmission FTIR spectroscopy. The products of acetaldehyde ozonation are shown to be different from pathways leading to acetic acid production during TEOS ozonation. Mechanistic pathways unique to Si-O-C containing species will be presented. The products formed upon introduction of boron and/or phosphorus containing precursors to the process flow will also be discussed.

10:20am SC1+EL+SS-MoM7 Thickness Control of an Ultrathin Oxide Film on Si(100)2x1 Synthesized by Ozone: A Kinetic Study on Initial Oxidation, *K. Nakamura, A. Kurokawa, H. Itoh, S. Ichimura,* Electrotechnical Laboratory, Japan

One of the alternative oxidants for the fabrication of an ultrathin silicon oxide film is ozone. Using highly concentrated ozone, we have succeeded so far in synthesizing an oxide film of 2nm on Si(100) at lower substrate temperature (for example, at 350°C). This oxide film has high density equivalent to that of a thermally grown oxide, much smaller thickness of

Monday Morning, October 2, 2000

structural transition layers, and can be obtained also by modifying and upgrading an already existing native oxide film.@footnote 1,2@ Moreover, the oxide thickness must be precisely and accurately controlled because of its practical use as a gate oxide film in MOSFET. In this paper, therefore, we will study growth kinetics of initial oxidation by ozone on silicon surfaces in detail. To fabricate an ultrathin silicon oxide film by ozone, clean Si(100)2x1 surfaces at between room temperature and 700°C were exposed to highly concentrated (>80%) ozone. Initial oxide growth was mainly monitored by x-ray photoelectron spectroscopy (XPS). The results indicate different kinetics on each oxide layer. Following to an adsorption on the surface investigated also by second harmonic generation (SHG), oxide growth on each of the first three oxide layers proceeded in accordance with Langmuir kinetics, indicating random adsorption on the active sites on each layer. Within this thickness, oxidation rates on the second and third layers possessed positive values of activation energy, while the growth rate on the first layer showed no activation barrier. Above this thickness, an oxide film by ozone grew in proportion to exposure time instead above the critical substrate temperature of 550°C. These suggest that control of film thickness should be optimized in the first three layers and above the fourth, respectively, due to different growth mechanisms. @FootnoteText@ @footnote 1@ K. Nakamura, S. Ichimura, A. Kurokawa, K. Koike, G. Inoue, and T. Fukuda, J. Vac. Sci. Technol. A 17 (1999) 1275. @footnote 2@ A. Kurokawa, K. Nakamura, S. Ichimura, and D. W. Moon, Appl. Phys. Lett. 76 (2000) 493.

10:40am SC1+EL+SS-MoM8 FTIR at Liquid/Solid Interfaces: In-situ Studies of HF Etching of SiO@sub 2@ on Si(100), *K.T. Queeney*, Smith College Department of Chemistry; *E.E. Chaban, Y.J. Chabal*, Bell Laboratories, Lucent Technologies

While much important semiconductor surface chemistry--cleaning, passivating and etching--takes place at the liquid/solid interface, the inherent difficulty of probing such interfaces has limited mechanistic understanding of these processes. We have developed a novel experimental setup that allows us to probe semiconductor/liquid interfaces with FTIR spectroscopy, circumventing the limitations of conventional multiple internal reflection spectroscopy to access the full frequency range of interest (850-4000 cm@super -1@), in particular the Si-O vibrational modes between 900 and 1250 cm@super -1@. We have used this capability to study in detail the etching in dilute hydrofluoric acid of SiO@sub 2@ on Si(100), lending new and valuable insight into the details not only of the chemical nature of the Si/SiO@sub 2@ interface, but also of structural aspects of the remainder of the film, including the SiO@sub 2@/air (water) interface. By analyzing spectra acquired sequentially during the etching process, we derive a layer-by-layer picture of the oxide spectral response; correlation of those spectra with changes in film structure are made via optical modeling. Varying the dielectric constant of the overlying medium (i.e. air versus water) allows quantification of spectral sensitivity to effects such as surface roughness. In addition, the in-situ nature of these studies allows us to evaluate the kinetics of the etching process and provides strong evidence for a structurally distinct layer near the Si(100) substrate, characterized by a marked change in vibrational signature, that is resistant to etching

Monday Afternoon, October 2, 2000

Semiconductors Room 306 - Session SC+EL+SS-MoA

Reactions on Semiconductors

Moderator: R.A. Wolkow, National Research Council of Canada

2:00pm SC+EL+SS-MoA1 Adsorption of SiH@sub 4@ on Si(001)(2x1) Investigated by Infrared Spectroscopy, *M. Shinohara*, *A. Seyama*, *Y. Kimura*, *M. Niwano*, Tohoku University, Japan

Adsorption of silane molecules, SiH@sub 4@ and Si@sub 2@H@sub 6@, onto Si(001) has so far been investigated extensively, because of the potential of using the silane molecules as the source gas for gas source molecular beam epitaxy (GS-MBE) for the growth of Si. Previous studies on Si deposition using silanes have suggested that during the course of Si crystal growth, silanes dissociatively adsorb on Si surface dangling bonds as trihydride (SiH@sub 3@) and dihydride (SiH@sub 2@) species and then decomposes to surface monohydride species, SiH. However, there has been only a little amount of information about the type of hydride species that are generated during the adsorption of silane on Si surfaces. In this study, we used infrared absorption spectroscopy (IRAS) in the multiple internal reflection geometry (MIR) to investigate the adsorption of SiH4 on the Si(001)(2x1) surface. IRAS-MIR provides us with valuable information about the hydrogen bonding configurations on semiconductor surfaces. Comparing infrared data with the density functional cluster calculation, we show that the silane molecule dissociatively adsorbs on Si(001)(2x1) to populate a dihydride (SiH@sub 2@) at the bridge site between two adjacent dimers and a monohydride species: the latter is formed by terminating the unsaturated dangling bonds of dimers by hydrogen atoms that are released from the silane molecule. We found that at high surface hydrogen coverage, surface silyl (-SiH@sub 3@) group and monohydride (SiH) species are generated. We interpret that at high hydrogen coverage, silane adsorbs onto a single dimer that has two unsaturated dangling bonds on which a hydrogen atom and a sylil group (-SiH@sub 3@) stick. We also show that a dihydride species that was initially generated by silane adsorption, dissociates even at room temperature and the released hydrogen atoms migrate on the surface to produce more monohydride species.

2:20pm SC+EL+SS-MoA2 Si(001):As Gas-source Molecular Beam Epitaxy: As Incorporation and Film Growth Kinetics, *H. Kim*, University of Illinois; *G. Glass*, PTD, Intel Corp.; *J.A.N.T. Soares*, University of Illinois; *P. Desjardins*, Ecole Polytechnique de Montreal; *J.E. Greene*, University of Illinois

Arsenic-doped Si(001) layers with concentrations C@sub As@ up to 5x10@super 18@ cm@super -3@ were grown on Si(001)2x1 at temperatures T@sub s@ = 575 - 900 °C by GS-MBE using Si@sub 2@H@sub 6@ and AsH@sub 3@. At constant flux ratio, C@sub As@ decreases, while the film growth rate R@sub Si:As@ increases, with T@sub s@. TPD measurements show that As segregates strongly to the growth surface and that the observed decrease in C@sub As@ at high T@sub s@ is primarily due to increasingly rapid arsenic desorption from the segregated layer. Decreasing T@sub s@ enhances As incorporation. However, it also results in lower R@sub Si:As@ due to higher steady-state As surface coverages which decrease the total dangling bond coverage and, hence, the Si@sub 2@H@sub 6@ adsorption rate. At constant T@sub s@, C@sub As@ increases, while R@sub Si:As@ decreases, with increasing AsH@sub 3@ flux. All incorporated As resides at substitutional electrically active sites for concentrations up to 3x10@super 18@ cm@super -3@, the highest value yet reported for Si(001):As growth from hydride source gases. D@sub 2@ TPD spectra exhibit @beta@@sub 1@ and @beta@@sub 2@ peaks associated with Si monodeuteride and dideuteride desorption as well as a new peak @beta@@sub 3@ attributed to desorption from Si-As mixed dimers. Steady-state arsenic surface coverages during film growth, and the As segregation enthalphy, were quantitatively determined as a function of C@sub As@ by comparison with As-adsorbed Si(001) reference samples with known As coverages. From AsH@sub 3@ adsorption kinetics and incorporation data, the AsH@sub 3@ reactive sticking probability on Si(001) was determined and As incorporation kinetics were quantitatively modeled. Initial experiments have demonstrated that temperaturemodulated growth can be used to increase both R@sub Si:As@ and C@sub As@ while providing layers which are atomically flat.

2:40pm SC+EL+SS-MoA3 Scanning Tunneling Microscopy of Impurity Dimers on Hydrogen-Terminated Si(100)-2x1 Surface, S. Matsuura, University of Tokyo, Japan; M. Fujimori, S. Heike, Y. Suwa, H. Kajiyama, T. Onogi, Hitachi, Ltd., Japan; K. Kitazawa, University of Tokyo, Japan; T. Hashizume, Hitachi, Ltd., Japan

We report a new dimer structure on a hydrogen-terminated n-type Si(100)-2x1-H surface found by a scanning tunneling microscopy (STM). The dimer structure is observed almost same as regular surface Si dimers at filled state, at empty state, however, is observed as different structure showing spatial variation of electronic density of states. Similar results were obtained in the case of As-doped surface. The surface density of the structures derived from measurement of the samples with different dopant concentrations was found to be proportional to the dopant density. Electronic structures calculated by first-principles calculations for a phosphorous dimer or an arsenic dimer on the Si(100)-2x1-H surface are in good agreement with the bias dependent STM images of the newly-found structure on the P-doped or As-doped Si(100) surface, respectively. We concluded that the dimer structure represents dopant atoms incorporated on the Si surface and forming a dimer. The calculation also revealed that the surface phosphorous and arsenic atoms are more stable forming dimers than being isolated on the hydrogen-terminated Si surface.

3:00pm SC+EL+SS-MoA4 Adsorption and Reaction of Fluorinated Fullerenes on Silicon, Y. Fujikawa, J.T. Sadowski, Tohoku University, Japan; K.F. Kelly, Pennsylvania State University; K.S. Nakayama, T. Sakurai, Tohoku University, Japan

The adsorption structure of fluorinated fullerene molecules deposited on silicon was studied using scanning tunneling microscopy (STM) and highresolution electron energy loss spectroscopy (HREELS). The results of HREELS indicated that the fluorine atoms around the molecules were detached from the molecules and chemisorbed to the surface. These fluorine adsorption sites were directly observed around the adsorbed molecules in the STM images. Some of the fluorine-adsorbed sites were found to form thread-like structures, suggesting that the molecules print the fluorine atoms on the terrace due to the rolling movement of the molecules. Annealing produced different degrees of defluorination of the fullerenes and etching of the silicon surface depending on the temperature. By imaging the intermolecular structure of the molecules with the STM, we can directly observe the loss of the fluorine atoms.

3:20pm SC+EL+SS-MoA5 STM Study of Self-Assembled Quantum-Dot Arrays of Sn on Si(111)-(7x7) Surface, *M. Yoon, R.F. Willis,* The Pennsylvania State University

The adsorption and diffusion mechanisms of Sn on the Si(111)-(7x7) at submonolayer coverages have been studied by scanning tunneling microscopy (STM). It is found that the preference of Sn adsorbates on the faultedhalves of the 7x7 unit cell is dependent on adsorbate coverage up to @THETA@ ~ 0.3 monolayer (ML). At higher coverages (~0.3 - 0.5 ML), the tin atoms cluster together on both halves of the 7x7 unit cell, forming a two-dimensional array of self-assembled quantum dots. This is in contrast to the behavior recently reported@footnote 1@ for Tl condensation on Si(111)-(7x7). In this latter case, the element occupies faulted half-cells preferentially and the surface remains metallic. In the present case, the Sn clusters are semiconducting, the surface showing an energy bandgap which increases with increasing coverage. The surface returns to metallic behavior as the number of Sn atoms approaches that of one monolayer of Si. @FootnoteText@ @footnote 1@L. Vitali, M. G. Ramsey, and F. P. Netzer, Phys. Rev. Lett. 83, 316 (1999).

3:40pm SC+EL+SS-MoA6 Evolution of Surface Morphology During Sb Growth on Ge(100), L.H. Chan, E.I. Altman, Yale University

Surfactants such as Sb have been found to promote layer-by-layer growth on metal and semiconductor surfaces. It is known that Sb and Ge intermix only at elevated temperature past 630K. Temperature programmed desorption was performed to study the energetics of Sb adsorption on Ge(100). The results demonstrated a typical high temperature peak that saturated at 1020 K before the appearance of a low temperature sublimation peak below 650 K with increasing Sb exposure. An additional high temperature peak at 1070 K was attributed to bulk incorporation of Sb. On a nominal 1 ML Sb covered Ge(100) surface prepared by deposition at 300K and annealing above the multiplayer desorption peak, scanning tunneling microscopy studies showed three surface layers were exposed. The images displayed bias dependent contrast suggesting the layers were not chemically uniform. To address the reasons for the morphology changes and to identify different components on the surface, a systematic study of Sb growth as a function of coverage and temperature was

Monday Afternoon, October 2, 2000

conducted. At room temperature, Sb adsorbs as tetramers and pairs of dimers. Several Sb@sub 4@ adsorption states are identified. Subsequent island growth leads to a poorly ordered surface with short strands of Sb dimer rows. The growth of longer dimer rows was interrupted by the growth of other nearby dimer rows randomly distributed on the Ge surface. Antimony incorporated into the top layer on either annealing or deposition at 600 K. Annealing gave well-structured dimer rows across the surface in all layers. However, intermixing of Sb and Ge at elevated temperature created ad-dimer clusters, vacancy islands, and reattachment of Sb and Ge ad-dimers on the top layer to the step edges. The implications of these results on surfactant-mediated growth will be discussed.

4:00pm SC+EL+SS-MoA7 Effects of Exposure on GaSe Passivated Si(111), J.A. Adams, A. Bostwick, S. Meng, B.R. Schroeder, M.A. Olmstead, F.S. Ohuchi, University of Washington

GaSe growth on Si(111) 7x7 between 500°C and 550°C results in the formation of a bilayer, which passivates the substrate dangling bonds and serves as the interface for further film growth. Ga sits directly atop surface Si, and the resultant interface bonding leaves Se lone-pair states on the surface, similar to Si(111):As. This makes the Si(111):GaSe surface resistant to contamination, and additional GaSe does not stick for T@sub substrate@@>=@500°C. We have studied the effects of exp osure to various atmospheric constituents on the electronic states and surface structure of the bilayer-passivated silicon surface using x-ray photoelectron spectroscopy and diffraction (XPS/XPD), low-energy electron diffraction (LEED) and ultraviolet photoelectron spectroscopy (UPS). We find that exposure to N@sub 2@ at atmospheric pressure has no apparent effect on the atomic or electronic structure and no N@sub 2@ is found to stick on the surface. However, we find that exposure to atmosphere for 5 minutes does change the surface states as observed from UPS, although LEED shows that the atomic structure of the GaSe bilayer does not change. The surface states can be almost completely recovered upon annealing at 500°C for 1 minute. Exposure to other atmospheric constituents such as O@sub 2@ and H@sub 2@O were also studied.

4:20pm SC+EL+SS-MoA8 Temporal Changes of Photoemission Spectra of the Alkali-metal-induced Ge(111) 3x1 Surface, G. Lee, Korea Research Institute of Standards and Science, Korea; C. Hwang, Korea Research Institute of Standards and Science; Y. Park, S. Cho, Korea Research Institute of Standards and Science; Korea; H. Lee, Korea Research Institute of Standards and Science; E. Cho, Chonnam National University, Korea

We investigated the temporal changes of the core-level photoemission spectra of the Ge(111)3x1 reconstructed surface induced by alkali metals (Li and Na) in UHV chamber. It is found that while the spectra from the Ge(111)3x1-Na surface is hardly affected, those from the Ge(111)3x1-Li surface change significantly in time. We identify that the changes of the core-level spectra from the Ge(111)3x1-Li surface are due to the contamination by residual oxygen gas in the chamber. The contamination rate of the Ge(111)3x1-Li surface is even higher than that of the clean surface, contradicting the expectation that alkali-metal-induced 3x1 reconstruction passivates the surface against oxidation. We discuss the difference in the contamination rate between the Ge(111)3x1 surfaces induced by different alkali-metal adsorbates.

4:40pm SC+EL+SS-MoA9 Role of Excited Electronic States in Reactions on Si(100), J.S. Hess, D.J. Doren, University of Delaware

Low-lying excited electronic states of the Si(100) surface can play a role in activated adsorption reactions. The nature of the lowest surface excited state and its coupling to the surface ground state will be described. Density functional theory calculations on cluster models of Si(100) have been used to predict the minimum energy difference between the optimized ground state and first excited state levels. The minimum energy crossing point between the two states was explicitly calculated, as was the spin-orbit coupling between them. The energy needed to reach the excited state surface is low enough, and the coupling between the states is strong enough, that crossing between the two states will be facile. The two states will be in thermal equilibrium and a significant population of the excited state is expected at typical reaction temperatures. The role of the excited state in selected reactions will also be discussed.

5:00pm SC+EL+SS-MoA10 Dynamics of Photo-induced Reaction on a Chlorinated Si(111) Surface, S. Haraichi, F. Sasaki, Electrotechnical Laboratory, Japan

In order to study photo-induced reaction of Si/Cl in the low fluence region, which is an influential candidate for low-damage manufacturing at the atomic level, the reaction mechanism was examined in terms of the photo-

excitation dynamics using femtosecond second-harmonic generation (SHG). SH signals on a clean 7x7 surface show a rapid dip induced by the pump beam, which is finished within several 100 fs. It is ascribed to charge transfer from the bulk Si to the 7x7 surface and subsequent surface recombination of photo-produced carriers through surface dangling bond states. The rapid dip is not seen on the chlorinated surface, because the surface dangling bond states are disappeared. With the increase of the pump beam power the decay profile of SH signals drastically changes and an upward peak clearly appears on the chlorinated surface. The upward peak is due to the precursor of surface reaction on the Si/Cl system. Though we observed both of photo-excitation SH dynamics on an n-type and a p-type Si surface, the difference was not found. The band bending near the chlorinated surface does not contribute to the reaction dynamics, because it is most likely that the photo-produced carriers immediately flatten the bands. We also observed the reaction dynamics dependence on the pump photon energy. The threshold pump power of the reaction induced by a 1.55 eV pump peam and a 3.1 eV pump beam were 45 mW and 4 mW, respectively. This difference is not only due to an absorption coefficient but also the excitation levels and the relaxation paths, because the upward peak position of SH dynamics was different in two pump photon energy.

Surface Science

Room 209 - Session SS2+EL-MoA

Electronic Structure and Excitations

Moderator: R.A. Bartynski, Rutgers University

2:00pm SS2+EL-MoA1 Recent Photoemission Studies of Quasi-1D Solids, K.E. Smith, J. Xue, L.C. Duda, Boston University; A. Fedorov, P.D. Johnson, Brookhaven National Laboratory; W. McCarroll, M. Greenblatt, Rutgers University INVITED

Much controversy surrounds the interpretation of the results of angle resolved photoemission spectroscopy (ARP) studies of the electronic structure of quasi one-dimensional (1D) solids. In principle, ARP should provide valuable information about quasi-1D solids, including the structure of the Fermi surface and possible non-Fermi liquid behavior of electrons close to the Fermi level (E@sub F@). In practice, straightforward interpretation of the spectra is often difficult. It has been reported that photoemission from states near E@sub F@ in guasi-1D conductors differs significantly from that measured from two and three dimensional solids. There are a number of possible explanations for these observations, including problems with surface defects and stoichiometry, charge density wave fluctuations leading to a pseudogap, or a Luttinger liquid state. We report here the results of a temperature dependent ARP study of the electronic structure close to E@sub F@ in the quasi-1D conductors Li@sub 0.9@Mo@sub 6@O@sub 17@ and K@sub 0.3@MoO@sub 3@.@footnote 1@ These materials are ideal for ARP studies since large high quality crystals can be grown, and surfaces suitable for ARP measurements can be prepared by cleaving in vacuum. Using very high momentum and energy resolution ARP, we clearly measured for both materials: i) quasi-1D bands dispersing across the Fermi surface; ii) substantial emission intensity at E@sub F@ in the metallic phase; and iii) a gap opening at E@sub F@ as the samples are cooled through the metal-semiconductor transition. Our results differ from many earlier ARP studies of quasi-1D solids. The differences are likely due to an order of magnitude improvement in angular resolution (and corresponding improvement in momentum resolution) for the spectrometer used here. The reported non-Fermi liquid behavior in photoemission from these solids will be discussed. @FootnoteText@ Supported in part by the DOE under DE-FG02-98ER45680 (KES) and DE-AC02-98CH10886 (PDJ).

2:40pm SS2+EL-MoA3 Fermi Contours and Adsorbate Phonon Anomalies for Li/Mo(110) and Li/W(110), *E. Rotenberg*, Lawrence Berkeley National Laboratory; *S.D. Kevan*, University of Oregon

Angle-resolved photoemission was used to measure the Fermi contours of surface-localized states on the Mo(110) and W(110) surfaces with varying amounts of adsorbed lithium up to 1 ML. In analogy with recent results for H on Mo and W(110), we find that the contours are well nested and therefore can drive a surface phonon anomaly. The nesting vector parallel to the @Sigma@ azimuth on Mo(110) at monolayer coverage is in good agreement with recent phonon measurements.@footnote 1@ We also report the variation of this nesting vector as a function of coverage, and show that a more complete understanding of the electron-phonon coupling on these surfaces might be obtained from coverage-dependent

Monday Afternoon, October 2, 2000

measurements of surface phonon dispersion relations. Finally, our results suggest even better nesting along the @Gamma@ --> S direction and that a more pronounced anomaly might be observed there. @FootnoteText@ @footnote 1@J. Kroger, D. Bruchmann, S. Lehwald, and H. Ibach, Surface Science 449(1-3),227 (2000).

3:00pm SS2+EL-MoA4 Thickness Dependence of the Unoccupied Electronic States in the Pd/Ru(0001) System, W.-K. Siu, T. Mensing, R.A. Bartynski, Rutgers University

The unoccupied electronic structure of the Pd/Ru(0001) system has been examined using inverse photoemission spectroscopy for Pd thicknesses in the 1 - 15 monolayers range. Previous studies indicate that in the submonolayer coverage range, the desorption temperature of CO on Pd/Ru(0001) is less than that of CO/Pd(111) or CO/Ru(0001). Similarly, we have previously shown that the desorption temperature for CO from the Cu/fccCo/Cu(100) metallic quantum well (MQW) system is a nonmonotonic function of film thickness and is correlated with MQW states crossing the Fermi level. This suggests that quantum size effects can influence the strength of the chemisorption bond. As Pd interacts more strongly with CO, our objective is to investigate the occurrence of MQW states in the Pd/Ru(0001) system and determine their influence in CO chemisorption. Metallic quantum well (MQW) states are observed at the @Gamma@ point of the Pd thin film. The energies of these states change as a function of the film thickness. A simple phase accumulation model provides a semiquantitative understanding of this behavior. There is also an unoccupied surface state at @Gamma@, which shifts to higher energy with increasing film thickness, approaching that of the single crystal Pd(111) surface state. We have also determined the energy dispersion with parallel momentum of the unoccupied Pd states along the @Gamma@K and @Gamma@M directions. Finally, the influence of MQW states on the adsorption of CO on the Pd/Ru(0001) system will be discussed.@footnote 1@ @FootnoteText@ @footnote 1@ Supported by NSF-DMR #98-01681 and ACS-PRF #33750-AC6,5.

3:20pm SS2+EL-MoA5 High Resolution Photoelectron Spectroscopy of Pu at the Advanced Light Source, D.A. Arena, J.G. Tobin, Lawrence Livermore National Laboratory; D. Shuh, E. Rotenberg, Lawrence Berkeley National Laboratory; J. Terry, R.K. Schulze, J. Lashley, T. Zocco, D. Farr, Los Alamos National Laboratory

High resolution photoelectron spectroscopy of Pu has been performed at the Spectromicroscopy Facility (Beamline 7.0) at the Advanced Light Source in Berkeley. Based upon an initial analysis of the data, two key results are immediately obvious. (1) The 5d-5f Resonant Photoemission of the Pu 5f levels exhibits a dependence upon the Pu phase and structure. For example, the results from alpha and delta Pu differ significantly. This strongly suggests that electronic behavior is linked to atomic ordering and structure in Pu. (2) Contamination with oxygen and carbon may be more insidious and subtle than initially believed. Photoemission measurements at a photon energy of 800eV exhibit oxygen and carbon core level peaks, while the same sample shows no contamination utilizing a photon energy of 1253eV, a typical laboratory source energy used in ECSA machines (i.e., Mg k-alpha). In other words, what was thought to be "clean" may not have been. Furthermore, contamination issues like these have a crucial impact upon interpretation of Pu core level spectra, e.g. localized and delocalized screening by 5f electrons. Additionally, 5f-6p Resonant Photoemission, core level spectra (particularly the Pu 4f's) and X-Ray absorption data, all from the Pu will be presented and discussed. Future plans, including ideas about studying magnetic effects in Pu, will also be described. UCRL-JC-133518 Abs.

3:40pm SS2+EL-MoA6 Plasmon Resonance Spectroscopy of Plutonium Metal Allotropes, R.K. Schulze, J.D. Farr, Los Alamos National Laboratory

We have measured the plasmon resonance response of the cleaned and well characterized surfaces of the six plutonium thermal allotropes (@alpha@, @beta@, @gamma@, @delta@, @delta@', @epsilon@) using backscatter electron energy loss spectroscopy (EELS). The energy of the plasmon resonance is highly dependent upon the electronic structure of the solid surface, and in particular, the density of electrons available for conduction. Using this method we probe directly, for the first time, the number of free elec trons, and the changes in the electronic structure of the plutonium. EELS spectra were acquired on a high purity sample of plutonium with primary electron beam energies of 150, 200, 500, 700, and 1000 eV, and with the sample at seven different temperatur es: -125 (@alpha@), 45 (@alpha@), 156 (@beta@), 250 (@gamma@), 410 (@delta@), 465 (@delta@'), and 525°C (@epsilon@). Changes in the plasmon resonance spectra over the 150 to 500 eV primary beam energy

range indicate that a surface reconstruction e xists for each of the Pu allotropes. The 700 and 1000 eV EELS measurements are alike, indicating that bulk characteristics are being probed at these energies. The bulk plasmon resonance energies for the allotropic series (@alpha@, @beta@, @gamma@, @delta@, @delta@', @epsilon@) are 12.23, 11.18, 11.16, 10.81, 10.94, and 10.92 eV. From these measurements, we extract the volume density of free electrons in each allotrope. In electrons per nm@super 3@ these are, for the series, 108.5, 90.7, 90.3, 84.8, 86.8, and 86.5. These results correlate directly with measurements of resistivity and magnetic susceptibility for the series of allotropes, indicating that the changes in free electron density are identically responsible for the changes in these physical properties. The implications of these results in terms of the electronic properties of Pu and in the changes of electronic structure between the allotropes will be discussed.

4:00pm SS2+EL-MoA7 Lifetimes of Conduction Band States at Semiconductor Surfaces, *Th. Fauster*, *M. Kutschera*, *C. Kentsch*, *M. Wiets*, *I.L. Shumay*, *M. Weinelt*, University Erlangen, Germany

In time-resolved two-photon photoemission electrons are emitted after absorption of two photons. By a suitable delay between the two photons the lifetimes of conduction band states can be directly measured in pumpprobe experiments. Using time-resolved two-photon photoemission we have studied several semiconductor surfaces. On the Si(100)-(2x1) surface several bulk and surface transitions with unoccupied intermediate states between the conduction band minimum and the vacuum energy are observed. Below the conduction band minimum we find a lifetime in the ps range, which we attribute to the unoccupied surface state. This unoccupied as well as the occupied surface state which originate from the silicon dangling bonds are clearly resolved within the same experiment. On epitaxial, metallic CoSi@sub 2@(111) films on a Si(111)-substrate three unoccupied states could be identified. Their lifetimes lie in the 10 fs range. Neither the lifetimes nor the energetic positions of those unoccupied states depend on the film thickness. On the SiC(0001)-(@sr@3x@sr@3)R30° surface the occupied and unoccupied Mott-Hubbard surface bands are observed. An asymmetric splitting relative to the Fermi level is found in agreement with recent theoretical calculations.

4:20pm SS2+EL-MoA8 Oscillating Band-bending at the Initial Stage of Sb Growth on Si(100) held at 60K, J.M. Seo, Chonbuk National University, Korea

Using the synchrotron photoemission spectroscopy, the band-bending, the work-function and the valence band edge were simultaneously monitored at the initial stages of Sb growth on Si(100) held at 60 K. By the intensity attenuation of Si 2p with increasing Sb coverage, it can be deduced that Sb forms a relatively uniform overlayer on Si(100) at 60 K. The band-bending, determined by the bulk Si 2p position, oscillates within 0.15 eV up to about 4 ML of Sb, while the corresponding work-function, monitored by the secondary-cutoff position of biased substrate, negligibly changes. The metallicity, monitored by the valence band edge, indicates that the surface becomes semiconductor-like up to about 1.5 ML but recovers its metallic character with additional Sb coverage. These results implicate that the oscillating band-bending is due to the local charge exchange between the dimer row and Sb at the interface, while the corresponding metallicity of Sb film is determined by the amount of confined and available charges within the film.

Electronics Room 312 - Session EL+NS-TuM

Molecular Electronics

Moderator: Y. Liang, Pacific Northwest National Laboratory

8:20am EL+NS-TuM1 Molecules, Hierarchical Assembly and Architecture of Moletronic Computers, W.L. Warren, Defense Advanced Research Projects Agency INVITED

While the rapid miniaturization of electronics has driven much of the development of computation and information systems, it is anticipated that future computational demands for performing calculations orders of magnitude faster with less power. To create discovery beyond silicon, the DARPA Moletronics program is proposing that both computational functionality and input/output architecture can be designed in molecular systems. These systems will high device density (scaleable to 10@super 12@ device/cm@super 2@) and be amenable to greatly simplified manufacturing fabrication using hierarchical-assembly. It is anticipated that architecture, a top-down approach will play an immense role in steering discovery. Moletronics is focussed on developing technologies based on the self-assembly of molecular components to act as devices, switches, and interconnects. The program does not clone contemporary electronic devices with molecular scale components, but rather create functionality that exploits what molecules are good at (self-assembly, thermodynamic equilibrium, and charge storage media.) The trick for molecular computers will be to cope with defects and to realize hierarchical processes to manufacture the hardware. Hierarchical assembly is envisaged as a set of processes that will first assemble individual devices, then create functional blocks (circuits) from those devices and finally assemble systems from the blocks. It is a bottom-up manufacturing process whereas current microelectronics fabrication is based on top-down manufacturing using lithography. The talk will discuss three over-riding themes of the Moletronics program: (1) molecular devices, (2) hierarchical assembly, and (3) architecture including defect tolerance and algorithm development to find the defects. @FootnoteText@ @footnote 1@ The contributions of the contractors of the DARPA Moletronics program and fellow program managers, Bruce Gnade, Christie Marrian, and John Pazik are gratefully acknowledged.

9:00am EL+NS-TuM3 Molecular Wires, Switches and Memories, J. Chen, Yale University INVITED

Molecular electronics has recently attracted much attention because of its potential application in future computational systems. Molecular wires and related strategically engineered structures (e. g., molecular switches and memories) offer an increased versatility in device design with reduced elements. Nanoscale molecular devices utilizing active self-assembled monolayer (SAM) as the active component will be reported. We will present results on: (1). measurements of through-bond conductance of symmetric metal/conjugated SAM/metal junctions where non-Ohmic thermionic emission was observed to be the dominant process, with isocyanide-Pd contacts showing the lowest thermionic barrier of 0.22 eV; (2). first realization of robust and large reversible switching behavior in an electronic device that utilizes molecules containing a nitroamine redox center (2'-amino-4,4'-di(ethynylphenyl)--5'-nitro-1-benzenethiolate) exhibiting negative differential resistance (NDR) and an on-off peak-tovalley ratio (PVR) exceeding 1000:1; while molecules containing a nitroonly redox center (4,4'-di(ethynylphenyl)-2'-nitro-1-benzenethiolate) exhibiting room temperature NDR; (3) demonstration of a two-terminal electronically programmable and erasable molecular memory cell with bit retention time greater than 10 minutes.

9:40am EL+NS-TuM5 Dissimilar Metal Electrodes with Nanometer Interelectrode Distance: Fabrication and Application to Characterizing Self-Assembled Molecular Electronic Devices, *M.A. Guillorn, I. Lee,* University of Tennessee; *D.W. Carr, R. Tiberio,* Cornell Nanofabrication Facility; *E. Greenbaum, J. Lee,* Oak Ridge National Laboratory; *M.L. Simpson,* Oak Ridge National Laboratory and The University of Tennessee In order to advance the state of molecular-scale electronics research,

electrode structures capable of realizing metal/molecular monolayer/metal heterojunctions have been fabricated using a variety of novel techniques that allow direct electrical contact with single molecules and small groups of molecules. By using Au as the electrode material, thiol-based selfassembly techniques have been successfully applied to deposit organicsynthetic molecules between these electrodes, thereby permitting their electrical characterization. This is possible due to the symmetry of these molecules. Unfortunately these techniques do not lend themselves to measuring the electrical properties of asymmetric molecules. An example of this type of molecule is the Photosystem I (PSI) reaction center which is of demonstrated interest to molecular-scale electronics research. Selfassembly techniques have been developed to preferentially orient the PSI with respect to a Au substrate, however, the polar nature of this molecule inhibits the use of this technique for the formation of Au/PSI/Au heterostructures. In this paper we will discuss a flexible and reproducible process for fabricating dissimilar metal electrodes with nanometer interelectrode distance (DiMEND) using high-resolution electron beam lithography and liftoff pattern transfer. This process is capable of realizing electrode pairs with a minimum interelectrode distance of less than 6 nm. This technique provides a reproducible method for creating lateral structures well suited for the electrical characterization of asymmetric molecules for molecular-scale electronics applications. Applications of this technology to characterizing self-assembled molecular electronic devices will be presented.

10:00am **EL+NS-TuM6** Characterization of Gold/Pentacene and Pentacene/Gold Interfaces, *Q.T. Le, S. Zorba, E.F. Forsythe, L. Yan, N.J. Watkins, Y. Gao,* University of Rochester; *S.F. Nelson,* Colby College; *C.S. Kuo, T.N. Jackson,* The Pennsylvania State University

Among the conjugated oligomers used as active materials in the fabrication of organic thin-film transistors (OTFT), pentacene is one of the most promising materials due to its high field-effect mobility. The performance of pentacene based OTFTs is now comparable to that obtained from hydrogenated amorphous silicon TFTs. The interface formed between the organic semiconductor and the conducting layer strongly influences the current-voltage characteristics of OTFTs. We report the interface formation between gold (Au) and pentacene using x-ray and ultraviolet photoelectron spectroscopy (XPS and UPS). The morphology of the pentacene film deposited on the substrate was measured using atomic force microscopy, showing a pentacene layer with small grain size. XPS results indicate that Au does not chemically react with pentacene if Au is deposited onto pentacene or if pentacene is deposited onto Au. For Au deposited on pentacene the UPS results show that there is an initial binding energy shift of both the highest occupied molecular orbital of pentacene and the vacuum level attributed to the formation of a common fermi level for the Au and pentacene as the Au is deposited. The initial increase is then followed by a decrease in binding energy shifts that is attributed to a reduction of the polarization energy caused by the formation of a Au overlayer on the surface of the pentacene. For pentacene deposited onto Au the UPS results show that there is only a shift of the vacuum level to lower binding energy.shift of the vacuum level to lower binding energy.

10:20am EL+NS-TuM7 Current-Induced Organic Molecule-Silicon Bond Breaking: Consequences for Molecular Devices, S.N. Patitsas, G.P. Lopinski, O. Hul'ko, D.J. Moffatt, National Research Council of Canada; R.A. Wolkow, National Research Council of Canada, Canada

The current carrying capacity of individual organic molecules covalently bound to silicon has been studied. Adsorbates comprised exclusively of saturated C-C bonds were found to be entirely stable whereas adsorbates containing pi-bonds could be controllably dislodged under modest conditions. The pi-bonds act as a chromophore, taking energy from a scattered electron, energy that can be selectively channeled into Si-C bond breaking. The class of adsorbates that are dislodged is closely related to unsaturated molecules widely investigated for enhanced molecular wire character. It is predicted that molecular devices containing such molecules will fail when operated. Measures to avoid current-induced bond breaking are described. New processes based upon the controlled bond breaking phenomenon are suggested.

10:40am EL+NS-TuM8 Molecular Arrays and Individual Dopants Studied by Ultrahigh Vacuum Scanning Tunneling Microscopy, *L. Liu*, *J. Yu*, *N. Viernes, M.C. Hersam, N.P. Guisinger, J.W. Lyding*, University of Illinois

One aspect of molecular electronics is the fabrication of atomically precise molecular arrays on silicon substrates. Feedback controlled lithography (FCL) is used in conjunction with UHV STM to create atomically precise templates for molecular adsorption. Cobalt phthalocyanine (CoPc) molecules have been sublimed onto these templates and subsequently imaged in the STM. The difference between filled state and empty state images is explained. Current imaging tunneling spectroscopy (CITS) of CoPc is also performed and discussed. CoPc Molecular symmetry as well as the feature associated with the central Co atom are studied in all STM images. CITS has also been used to identify and study individual dopants on or near

Si(100)2X1:H surfaces. For high quality UHV H-passivated Si(100) the Fermi level is unpinned at the surface, thus enabling the observation of subtle features including subsurface dopants. For example, boron atoms appear as slight hillocks in filled state images and as centro-symmetric depressions in empty states. Full CITS data sets and their analysis and interpretation will be presented. The same techniques will be used to present results for isolated Si dangling bonds created by FCL.

11:00am EL+NS-TuM9 Direct Measurements of Electrical Transport through DNA Molecules, D. Porath, Tel Aviv University, Israel & Delft Univ. of Tech., The Netherlands, Israel; A. Bezryadin, Harvard University; S. de Vries, C. Dekker, Delft University of Technology, The Netherlands INVITED Is DNA a conductor for electrical charges? This question has been heavily debated over the past few years, spurred by optical experiments that measured fluorescence quenching for DNA molecules and recent electrical measurements. Here we present measurements of electrical transport through short and well-defined DNA molecules that show large-gap semiconducting behavior. A 10.4 nm long, double-stranded poly(G)-poly(C) DNA molecule is connected to two metal nanoelectrodes that are separated by 8 nm. Nonlinear current-voltage curves with a voltage gap at low bias are observed at ambient conditions as well as in vacuum and at cryogenic temperatures. The voltage dependence of the differential conductance exhibits a peak structure, suggesting that transport of charge carriers is mediated by the molecular energy bands of DNA. Recent STM measurement on similar DNA molecules will be shown as well.

11:40am EL+NS-TuM11 Whole-Cell Bio-computing in a Microelectronic Format, *M.L. Simpson*, Oak Ridge National Laboratory and The University of Tennessee; *G.S. Sayler, J. Fleming, B. Applegate, S. Ripp, D. Nivens,* University of Tennessee Center for Environmental Biotechnology

Even simple cells perform tremendously complex information processing operations involving memory (genes), sensing and feedback (promoters, regulatory proteins), and in some cases, interconnectivity (quorum sensing). For example, Escherichia coli, with a 4.6 million base-pair chromosome, has the equivalent of a 9.2-megabit memory to code for as many as 4,300 different polypeptides under the inducible control of perhaps several hundred different promoters. Yet, all of this functionality is contained in an area of approximately 1 square micron. Conversely, current predictions of the future of silicon integrated circuits indicate that 1 square micron of silicon will contain only a 245 bit memory or 1.66 simple logic gates by 2014. Obviously, silicon technology will not approach bacterialscale integration within the foreseeable future. Furthermore, microorganisms have some qualities that are quite desirable for information processing devices and systems. Bacterial cells are relatively rugged "devices" that subsist in even extreme environments. Also, they are fairly easy to manipulate genetically, and have a diverse set of gene regulation systems. Furthermore, cells easily can be incorporated into a 3dimensional structure instead of the planar structure of integrated circuits. And finally, cells self-assemble and self-replicate, and therefore are easy to manufacture. We will present our work to incorporate the information processing capabilities of living cells into a microelectronic format. This will include our work on the bioluminescent bioreporter integrated circuit (BBIC) for sensing applications, as well as our recent work to engineer more complex information processing and communication functions into whole cells deployed on integrated circuits.

Semiconductors

Room 306 - Session SC+EL+SS-TuM

Compound Semiconductors

Moderator: J.W. Rogers, Pacific Northwest National Laboratory

8:20am SC+EL+SS-TuM1 Reconstructions and Steady-state Surface Structures on InAs(001)-(2x4): Implications for Atomistic Modeling of Growth, W. Barvosa-Carter, F. Grosse, HRL Laboratories and University of California, Los Angeles; M. Gyure, HRL Laboratories; J.H.G. Owen, C. Ratsch, HRL Laboratories and University of California, Los Angeles; R.S. Ross, J.J. Zinck, HRL Laboratories

Heterostructures involving InAs, GaSb, and AlSb are increasingly finding applications in high-frequency, infrared, and 'spin-tronic' devices. Interface structure in these devices can be critical in determining device performance. The robustness of any model that seeks to relate process parameters and in-situ sensor signals to the surface chemistry or roughness of the growing film ultimately depends on our understanding of the relevant surface reconstructions and epitaxial growth mechanisms. Using MBE, RHEED, and atomic-resolution STM, we have studied the reconstructions and 'steady-state' surface structures present on MBEgrown InAs homoepitaxial surfaces in the (2x4) growth regime. On InAs we find two reconstructions that are relevant for growth: the familiar @beta@2(2x4) (as on GaAs) and the less familiar @alpha@2(2x4). We find excellent agreement between detailed atomic-resolution STM and firstprinciples simulated images of these structures. Upon quenching, we find that "steady-state" InAs surfaces exhibit small islands and adatom-like structures residing on a disordered mixture of the @beta@2 and @alpha@2 reconstructions, and that the proportions of these structures vary as a function of As pressure and temperature. Hence, the growth surface structure for InAs is remarkably different than for GaAs, where only the @beta@2 reconstruction is present with relatively few defects under device growth conditions. These results are in excellent qualitative agreement with an ab initio-based Monte Carlo model that is being developed in parallel with the experimental effort to describe reconstructions and growth on this surface.

8:40am SC+EL+SS-TuM2 Oscillations of Local Density of States at the Epitaxially Grown InAs(111)A Surfaces Characterized by Low-temperature Scanning Tunneling Microscopy, K. Kanisawa, M.J. Butcher, H. Yamaguchi, Y. Hirayama, NTT Basic Research Laboratories, Japan

The characterization of semiconductor surface electrons is very important for understanding microscopic electron behavior. Though the local density of states (LDOS) has been studied at metal surfaces by using lowtemperature scanning tunneling microscopy (LT-STM), the only studies that have been reported for semiconductors are on cleaved (110) surfaces. A LT-STM study of an epitaxial semiconductor surface makes it possible to compare the electron behavior directly with nanometer-scale morphology. We have performed a LT-STM study of the epitaxially grown InAs(111)A surface on the GaAs(111)A substrate in layer-by-layer growth mode at 5 K. Topographic and dI/dV images were obtained simultaneously by using a lock-in technique. In the dI/dV images, LDOS oscillation patterns were clearly imaged at surface defect sites, which were identified in the corresponding STM images. At an isolated defect, clear LDOS Friedel oscillations made of concentric circles were observed. From the dependence of the oscillation period, the effective mass was calculated to be 0.043m@sub 0@, which is consistent with that of InAs with a relatively high electron concentration. In the case of steps with a height difference of integral monolayers, the oscillation patterns showed dark bands along the steps. In contrast the Frank partial dislocations, with height differences of fractional monolayers, showed bright bands. This implies that there are large differences between the electron scattering phases at the steps and at the dislocations. During the InAs growth, triangular regions are formed on the surface by three {111} stacking fault planes. Such boundaries showed symmetric and regular patterns inside. Our detailed analysis suggests that these patterns are related to zero-dimensional electron systems confined within the InAs nanostructures.

9:00am SC+EL+SS-TuM3 Something Old, Something New, Something Borrowed, Something BLUE - Fifty Years of III-V Compound Semiconductors!, R.D. Dupuis¹, University of Texas, Austin INVITED III-V compound semiconductors, first identified in 1950, have become critically important for the commercial development of advanced semiconductor devices and systems. In the past fifty-some years, many workers from all over the world have contributed to this outstanding success. The epitaxial growth of III-V films began in 1960 with the early work of Holonyak who used iodine transport in a closed tube to produce epitaxial layers of GaAs/GaAs, GaAs/Ge, and various GaAsP alloys. Opentube VPE and LPE for III-Vs were developed soon after this work. In 1967, Manasevit, et al., demonstrated the metalorganic chemical vapor deposition (MOCVD) epitaxial growth process and in 1970 Cho, et al. reported the first molecular beam epitaxy (MBE) growth of GaAs. Thus, twenty years after the first identification of III-Vs as semiconductors, all of the epitaxial growth processes we use today had been developed. It has taken 30 more years of technological and scientific advances to arrive at the understanding of these materials that we take for granted today. In fact, much of the new advanced communications systems that will be employed in the next 10 years depend fundamentally upon III-V epitaxial growth. In this talk, I will briefly review some aspects of the history of the development of these material systems and growth processes and I will discuss some of the recent results as well as speculate on the future development of III-V compound semiconductor materials.

9:40am SC+EL+SS-TuM5 Strain-Induced Anisotropy of Gallium Phosphide Islands on Gallium Arsenide, *C.H. Li*, University of California, Los Angeles; *L. Li*, University of Wisconsin, Milwaukee; *Q. Fu*, *M.J. Begarney*, *R.F. Hicks*, University of California, Los Angeles

We have undertaken a study to produce ordered nanostructures on compound semiconductor surfaces by the heteroepitaxial growth of highly strained island structures. Phosphorous-rich (2x4) islands are produced by decomposing phosphine on gallium arsenide (001)-(4x2) surfaces in ultrahigh vacuum. These islands exhibit anisotropy of approximately 10 to 1 with the (2x4) domains dramatically elongated along the [110] direction. The island width increases with the phosphorous coverage from 24 @Ao@ at 0.1 ML to 48 @Ao@) at 0.75 ML. This is attributed to strain induced by the lattice mismatch of phosphorous dimers on gallium arsenide. The implication of this finding to the epitaxial growth of GaP/GaAs heterostructure will be discussed at the meeting.

10:00am SC+EL+SS-TuM6 Relative Reactivity of Arsenic and Gallium Dimers and Backbonds during the Adsorption of Molecular Oxygen on GaAs(100)(6x6), *P. Kruse, J.G. McLean, A.C. Kummel,* University of California, San Diego

The semiconductor industry has a strong interest in understanding and employing the reactions of oxygen with III-V materials for fabrication of GaAs CMOS devices. We have monitored the initial stages of the chemisorption of molecular oxygen on the GaAs(100)(6x6) reconstructed surface by means of room temperature scanning tunneling microscopy. This surface is terminated by both gallium dimers and arsenic dimers, allowing for a direct comparison of their reactivity. Neither the As nor Ga dimer bonds react with thermal molecular oxygen. Likewise, the Ga-As back bonds of the Ga dimers do not exhibit any reactivity. Instead, the chemisorption proceeds with 100% chemical selectivity via the reaction of molecular oxygen with the As-Ga back bonds of the As dimers. The interaction between the highly electronegative oxygen atoms and the surface is initiated through the high electron density at the arsenic atoms. One oxygen atom displaces the attacked arsenic atom while the other oxygen atom bonds to two neighboring gallium atoms, resulting in the thermodynamically most stable reaction products: metallic arsenic clusters and gallium oxide.

10:20am SC+EL+SS-TuM7 Role of Ligand Termination in Atomic-Layer-Controlled Growth, R.M. Osgood, N. Camillone III, Y. Luo, M. Han, Columbia University INVITED

We describe employment of a series of in situ UHV diagnostics to study the surface chemistry of ligand capping in limiting reactions for atomic-layerdefined growth of semiconductor thin films. In the study, molecular precursors were on surfaces held at temperatures from 180-300K in a UHV chamber. The terminating groups, formed by the dosing, were identified and their chemistry investigated using thermal desorption spectroscopy, NEXAFS, Auger, spectroscopy, and LEED. Using CdS growth on ZnSe(100) as the model system, we have found that CH@sub 3@ and H terminal groups deposited by reactions with Cd(CH@sub 3@)@sub 2@ and H@sub 2@ S, respectively, effectively limit growth precisely on all except the first monolayer. A study of intermixing in the first layer shows clearly the role of surface temperature in controlling the reaction chemistry and coverage of terminating species. The implications with regard to atomic-layer-controlled growth of other systems will also be discussed.

11:00am SC+EL+SS-TuM9 Two-step MOCVD Growth of Piezoelectric ZnO Thin Film on SiO@sub 2@/Si Substrates, S. Muthukumar, N.W.

Emanetoglu, G. Patounakis, C.R. Gorla, S. Liang, Y. Lu, Rutgers University ZnO is a wide bandgap semiconductor with a direct bandgap of 3.3eV. Piezoelectric ZnO has high electro-mechanical coupling coefficient. Thin film piezoelectric ZnO deposited on semiconductor substrates is used for surface and bulk acoustic wave (SAW & BAW) devices, which offer advantages such as low power consumption, circuit miniaturization and cost reduction by integration with main stream MMIC technology. Furthermore, temperature compensation may be achieved in the ZnO/SiO2/Si system as ZnO and Si have positive temperature coefficient of delay (TCD), while SiO2 has negative TCD. Temperature compensated SAW devices are attractive for both communication and sensor technologies. In the present work, ZnO thin films were grown on SiO2/Si substrates by MOCVD. The structural properties of the films were investigated using XRD, SEM, and scanning probe microscopy. The films grown at 300°C were dense and had a smooth surface morphology, but poor crystallinity. In contrast, the films grown at 500°C were predominantly c-oriented, but had a rough surface. A two-step growth process was developed to obtain films with both good crystallinity and smooth surface. A high temperature (450500°C) buffer layer was initially deposited, to provide a highly crystalline template for the subsequent low temperature (300-330°C) growth. Annealing was done on the thin films in N2 and O2 ambient for different durations to improve film resistivity, essential for fabricating low-loss SAW devices. The SAW velocity, coupling coefficient and TCD of the ZnO/SiO2/Si system were investigated through modeling and computer simulation based on Adler's transfer matrix method and Green's function analysis. The test devices with the proper ZnO and SiO2 thickness exhibited multiple temperature compensated frequency points in the 1.42 GHz to 2.15 GHz range. These results show that temperature compensated ZnO/SiO2/Si system is promising for fabricating low-loss SAW devices.

11:20am SC+EL+SS-TuM10 Spontaneous Island Formation Caused by Reconstruction Changes During III-Sb Homoepitaxy@footnote 1@, A.S. Bracker, B.Z. Nosho, B.R. Bennett, J.C. Culbertson, B.V. Shanabrook, L.J. Whitman, Naval Research Laboratory

Most III-V semiconductor surfaces exhibit reconstructions with compositions that differ from the bulk material. These nonunity III:V stoichiometries constitute an inherent source of interfacial roughness during molecular beam epitaxy when the reconstruction changes during growth. This issue is especially important for the AISb and GaSb(001) surfaces, because several reconstructions exist over the range of substrate temperatures and beam fluxes typically used for growth. For AISb, the relevant reconstructions include @alpha@(4x3), @beta@(4x3). @gamma@(4x3), and c(4x4), in order of increasing Sb:Al coverage.@footnote 2@ We have used scanning tunneling microscopy (STM) and reflection high-energy electron diffraction (RHEED) to characterize how the initial stages of homoepitaxy depend on the surface reconstruction and growth conditions. When the growth conditions cause a transition between reconstructions, islands spontaneously form on the surface. In addition to roughening an otherwise flat surface, these islands change the island size distribution during subsequent growth. Unfortunately, the RHEED patterns for the three (4x3) surfaces all have a similar streaky (1x3) symmetry during growth, making it difficult to optimize growth conditions based on this diagnostic alone. However, because of its sensitivity to surface roughness, RHEED intensity oscillations may be used to monitor the reconstruction-mediated roughening. We will discuss the realistic growth situations where this type of roughening should be important. @FootnoteText@ @footnote 1@This work was supported by ONR and DARPA. @footnote 2@Barvosa-Carter et al., Phys. Rev. Lett. 84, 4649 (2000).

11:40am SC+EL+SS-TuM11 Photon-activated Electron-Transfer-Reaction Surface Modification of GaAs(001), *N. Camillone III*, *K.A. Khan*, Columbia University; *J.A. Yarmoff*, University of California, Riverside and Lawrence Berkeley National Laboratory; *R.M. Osgood*, *Jr.*, Columbia University

UHV methods for adjusting the reconstruction and composition of the top layer of atoms on a semiconductor surface are expected to have important implications for precise control of growth surfaces and surface reactions. In this talk we will describe a transformation of the surface reconstruction resulting from a photoinduced electron transfer reaction occurring thereupon. We have carried out preliminary studies which demonstrate that variation in photon exposure and thermal treatment allows the surface reconstruction to be controllably adjusted from the Ga-rich c(8x2) to the (4x6), (3x1) and As-rich c(2x8) terminations. The modification of the reconstruction is the result of a modification of the surface stoichiometry due to the extraction of surface Ga atoms as a result of reaction with bromine. The bromine is produced at the surface by photoinitiated dissociative electron attachment to methyl bromide molecules physisorbed in a single monolayer at \sim 90 K. Subsequent to the photoinduced surface reaction, the gallium is removed by annealing to desorb a gallium bromide product. A comparison of the results obtained with low energy electron diffraction, temperature programmed desorption and energy-resolved photofragment angular distribution measurements shows that the most As-rich surface obtained by our technique is identical in structure to that of a control surface prepared using the standard iodine thermal reaction method. In principle, the use of this photon-activated reaction, and others like it, could allow for precise patterning of the surface structure based on control of photon or electron exposure, molecular coverage, thermal treatment and lateral patterning of the incident photon or electron beam.

Surface Science

Room 209 - Session SS2+NS+BI+EL-TuM

Self-Assembled Monolayers

Moderator: D.H. Fairbrother, Johns Hopkins University

8:20am SS2+NS+BI+EL-TuM1 Creating Highly Selective Organic Surfaces using Self-assembly: A New Family of Organothiols, *R. Arnold*, Ruhr-Universität Bochum, Germany; *A. Terfort*, Universität Hamburg, Germany; *C. Wöll*, Ruhr-Universität Bochum, Germany

The creation of organic surfaces with specific properties via the adsorption of correspondingly functionalized organothiols has recently attracted considerable interest, e.g. in the context of bio-sensors and biomimetics. In case of alkanethiols some functional groups, however, interact so strongly with each other that the ordering within the SAMs is affected, e.g. in the case of -COOH functional groups.@footnote 1@ The situation can be improved by using more rigid backbones, e.g. oligophenyl units.@footnote 2@ With regard to biochemical applications in many cases the distance between adjacent organothiol units (4.97 Å) is too small to immobilize larger molecules, e.g. small proteins. In the past these problems could be overcome in some cases by diluting the functionalized organothiol in a shorter, nonfunctionalized thiol. Here, we present a different approach where a more bulky thiol is used, which increases the nearest neighbor distance. We will present the results of a study using several homologues of triptycenethiols. SAMs formed from these compounds were characterized by using XPS, IRRAS, NEXAFS, LEED and TDS. The results reveal the formation of well ordered monolayers, which are anchored to the gold surface in a more distant lateral structure than alkane- or pterphenylthiols. @FootnoteText@ @footnote 1@ Dannenberger, O.; Weiss, K.; Himmel, H.-J.; Jäger, B.; Buck, M.; Wöll, C. Thin Solid Films 1997, 307, 9885-9893 @footnote 2@ Himmel, H.-J.; Terfort, A.; Wöll, C. J. Am. Chem. Soc. 1998, 120, 12069-12074.

8:40am SS2+NS+BI+EL-TuM2 Characterization of the Alkanthiol/Metal Interface by High Resolution Core Level Spectroscopy, K. Heister, H. Rong, M. Buck, University Heidelberg, Germany; L. Johansson, University Karlstad, Sweden; M. Zharnikov, M. Grunze, University Heidelberg, Germany

During the last decade X-ray Photoelectron Spectroscopy with a laboratory X-ray source became a conventional technique to characterize thiol derived SAMs. However, due to the mostly poor energy resolution, a strong attenuation of the photoelectron signal, and a low photoionization crosssection of the relevant core levels at high photon energies a precise binding energy analysis of an important building block of a SAM, the SAM/metal interface was hardly possible, even though high resolution photoelectron spectroscopy could give important information about the chemical state of the atoms in this region. Taking advantage of the high performance and tunebility of the third generation synchrotron sources we have firstly applied the synchrotron-based High Resolution Core Level Spectroscopy to study the SAM/metal interface. The variable photon energy of the synchrotron light and a high energy resolution of the spectrometer (0.1-0.3 eV) enabled us to resolve the bulk and surface components of the substrate emission peak (Au 4f / Ag 3d) and monitor the evolution of these components upon the alkanethiol and biphenylthiol adsorption. Simultaneously, the interaction of the thiol-derived molecules with the substrate was followed by monitoring the S2p doublet attributed to the sulfur head group of these molecules. Only one sulfur species was found in the densely packed SAMs, which implies an equivalent bonding geometry for all adsorbed molecules. In SAMs comprising of specially designed, mixed aliphatic-aromatic molecules a periodical, 'odd-even' shift of the S2p binding energy with the varying length of the aliphatic part was observed. This shift can be attributed to the distortion of the substrate-S bonding angle resulting from the unfavorable package conditions occurring at definite lengths of the aliphatic part. This work has been supported by the German Bundesministerium für Bildung, Wissenschaft und Technologie through grant No. 05 SL8VHA 2 and by DAAD.

9:00am SS2+NS+BI+EL-TuM3 The Influence of the Endgroup and the Chain Length on the Growth of CH@sub 3@- and CF@sub 3@-terminated Alkanetiols on Au(111), J. Pflaum, Princeton University; G. Bracco, University of Genova, Italy; G. Scoles, Princeton University; R. Lee, University of Houston; A. Kahn, Princeton University

The influence of the functional endgroup and the CH@sub 2@ chain length on the growth of alkanethiols on Au(111) was studied by scanning tunneling microscopy (STM) and x-ray surface diffraction in grazingincidence geometry (GIXD). Thiols are model systems for self-assembled monolayers (SAMs) and exhibit a complex phase diagram as function of

coverage. The structure and the electronic properties of the SAMs are determined by the sulfur headgroup, the CH@sub 2@ backbone and the functional endgroup. Leaving the sulfur headgroup unchanged, we studied how the film structure depends on the endgroup by comparing CH@sub 3@- and CF@sub 3@-terminated thiols. All films were prepared from solution on an atomically ordered Au(111) surface. The lateral order of the as-grown CH@sub 3@-terminated films corresponds to the c(4x2) phase, i.e. the highest density standing-up phase. From STM studies we conclude that the arrangement of CH@sub 3@ endgroups corresponds to a pinwheel-like structure rather than to a zig-zag-like structure. In contrast, CF@sub 3@(CH@sub 2@)@sub 9@SH showed no lateral ordering as seen by STM and GIXD. However, the difference between electron densities at the CF@sub 3@/vacuum and the SH/Au interfaces induces an oscillation of the GIXD reflectivity. Fitting the periodicity of the modulation using the Parratt formalism leads to an estimate of the film thickness and its roughnesses at both interfaces. In spite of the lack of lateral order the film appears to be made by standing-up molecules. Differences between the thickness measured by ellipsometry and x-rays will be discussed. We will also explore the lying-down phase of alkanethiols and fluorinated thiols as organic templates for organic heterostructures. Initial results on the growth of PTCDA on such templates will be presented. This work was supported by the MRSEC program of the National Science Foundation (DMR-9809483). J.P. thanks the Deutsche Forschungsgemeinschaft for support (Grant No. PF 385/1-1)

9:20am SS2+NS+BI+EL-TuM4 Self-Assembled Monolayers of Terphenyl Derivatized Thiols; Adsorption, Insertion Process and Electrical Conduction, *T. Ishida*, JRCAT-NAIR and PRESTO-JST, Japan; *W. Mizutani*, JRCAT-NAIR, Japan; *N. Choi*, JRCAT-ATP, Japan; *H. Tokumoto*, JRCAT-NAIR, Japan

The investigation of SAMs made from conjugated molecules is highly activated from a viewpoint of molecular electronics as well as stable SAM formation. In the present study, we have investigated an insertion process of conjugated molecules, terphenylthiol (TPO), terphenyl methanethiol (TP1), terphenyl propanethiol (TP3), into nonanethiol self-assembled monolayers (SAMs) on Au(111) by STM. STM observation revealed that the insertion process is dependent on the molecular length of conjugated molecules. At the initial stage of insertion, replaced area of TP1 is larger than those of TPO and TP3. However, when the immersing time is more than 12h, the replaced area of TP3 is larger than those of TP0 and TP1. The insertion process is likely to be determined by the solubility of the conjugated molecules and thermal dynamics. The single molecular resistance were increased with the number of the methylene groups, and obtained about 20G-ohm (TP0), 40 G-ohm (TP1) and 66 G-ohm (TP3). The vertical conduction of the conjugated molecular domains of TP1 and TP3 depended on their lateral sizes, while strong dependence was not observed in the case of TPO, suggesting that methylene group is necessary between the sulfur and aromatic rings to increase the vertical conduction of molecular domain.

9:40am SS2+NS+BI+EL-TuM5 Structure and Chemistry of Alkanethiol Self-Assembled Monolayers, G.E. Poirier, T.M. Herne, C.C. Miller, M.J. Tarlov, National Institute of Standards and Technology INVITED

Derivatized alkanethiols form dense, physically blocking films on Au surfaces thereby providing an effective and parsimonious method to control the chemical, physical, and electron-transfer properties of electrode surfaces. To predict the function of these monolayers in device applications, scientist require an understanding the molecular-scale structure and chemistry. Our structure studies were conducted using gasphase transport of decanethiol onto clean Au(111). Characterization was accomplished using ultrahigh vacuum scanning tunneling microscopy. At low surface coverage, decanethiol exists as a 2-dimensional gas. With increasing coverage the molecules sequentially condense into islands of three discrete commensurate crystalline lattices, each characterized by alignment of the molecular axes with the surface plane (striped phases). Above saturation coverage of the densest striped phase, the monolayer undergoes an edge-mediated melting transition forming a supercooled 2dimensional liquid. Domains of the c(3x2*3) phase, characterized by alignment of the molecular axes close to the surface normal, nucleate and grow from this surface liquid. The reaction of these monolayers with ozone was characterized using scanning tunneling microscopy and x-ray photoelectron microscopy; our results show that exposure to ozone results in oxidation of the thiol terminus. The reaction initiates at the c(3x2*3) domain boundary network and propagates into the domains. Above a threshold surface oxygen content, the monolayer converts to a twodimensional fluid that can subsequently recrystallize to a commensurate

monolayer of partially oxidized thiol. Further exposure to ozone results in conversion of the monolayer to a fluid phase and a 10% to 30% expansion of the Au lattice at the Au-thiol interface with concomitant formation of Au islands. Our results demonstrate that crystallographic defects in monolayer films can play an important role in their chemical reactions.

10:20am SS2+NS+BI+EL-TuM7 Characterization of SAMs with Contrast Variation SPR Technique, K. Tamada, NIMC and RIKEN Frontier Program, Japan; H. Akiyama, J. Nagasawa, NIMC, Japan

We report characteristics of azobenzene-containing self-assembled monolayers (SAMs) which is designed and synthesized for surface photoisomerization reaction. The surface reaction was monitored by Surface Plasmon Resonance Spectroscopy (SPR), in which the contrast variation technique with various organic solvents was used to improve the accuracy for determination of the optical thickness change by surface reaction. The SAM formation was monitored by kinetic mode experiment with SPR in 0.1mM hexane solution, and after rinsing, refractivity change by UV-VIS photo irradiation was studied in various solvents. In this study, hexyl azobenzene thiol (12-(4-((hexylphenyl)azo)phenoxy)dodecane-1-thiol) SAM was used as an unreactive surface and unsymmetrical azobenzenedisulfides SAMs with the same azobenzene functions were used as reactive ones. Following the previous reports, monomeric dispersion of dye function with disordered chains seems to be necessary to realize highly reactive surface. For our unsymmetrical azobenzene-disulfides SAMs, the free volume for photo-isomerization reaction are guaranteed by 50% dilution of dye functions on surface at monomolecular level. As a result, it was confirmed that unsymmetrical azobenzene-disulfides SAMs were highly reactive, especially, in good solvents (alkanes: C5, C6, C7, C8) and the length of alkyl side chains was quite efficient for surface reactivity.

10:40am SS2+NS+BI+EL-TuM8 Characterization of a Polymerized Self-Assembled Monolayer Using NEXAFS, A.L. Marsh, D.J. Burnett, University of Michigan; D.A. Fischer, National Institute of Standards and Technology; C.E. Evans, J.L. Gland, University of Michigan

Near-edge X-ray Absorption Fine Structure, or NEXAFS, at the C-K-edge was used to characterize the orientation of the polymeric backbone in a selfassembled monolayer of 15,9-polydiacetylene. Monolayers were fabricated from the assembly of molecules of dinonacosa-10, 12-diyn-disulfide from a chloroform solution onto a 2000 Angstrom gold film on a mica substrate. Polymerization occurs across one of the C-C triple bonds in the chain, which results in a polymeric network located within the monolayer. Since resonance intensities in NEXAFS spectra are dependent on electric dipole selection rules, it is possible to determine the orientation of the polymeric backbone by comparing spectra at normal incidence (E vector parallel to the surface plane) with spectra at glancing incidence (E vector perpendicular to the surface plane). From the two spectra it was determined that the polymeric backbone is oriented parallel to the surface, while the alkyl chains are oriented perpendicular to the surface. Since NEXAFS probes unfilled molecular orbitals, it is capable of distinguishing between various bonds, i.e. a C-C double bond versus a C-C triple bond, making it possible to determine structural changes as a function of temperature. Upon increasing the temperature, the C-C double bond pi* resonance increases, while the C-C triple bond pi* resonance decreases. These changes would be consistent with a degradation of the polymer backbone. Above a threshold temperature, the changes are irreversible, leading to eventual thermal degradation of the monolayer.

11:00am SS2+NS+BI+EL-TuM9 An Estimation of Effective Mean Free Path of Photo- and Auger Electrons in Partial Yield Measurements using Selfassembled Monolayers, *M. Zharnikov*, *S. Frey, K. Heister, M. Grunze*, Universität Heidelberg, Germany

In the partial electron yield (PEY) acquisition mode commonly used in X-ray absorption spectroscopy both elastically and inelastically scattered electrons contribute to the signal with the latter contribution presumably dominating. In this case a majority of inelastic scattering events will not result in the signal attenuation as it happens in the X-ray photoelectron spectroscopy (XPS). The scattered electrons will still have a kinetic energy in the acquisition range of the spectrometer. The related values of mean free path (MFP) should be, therefore, noticeably larger than the well-known inelastic mean free paths for electrons of definite kinetic energy. We have performed XPS and near edge X-ray absorption fine structure (NEXAFS) spectroscopy measurements for series of self-assembled monolayers of alkanethiols on gold substrate. The length of the alkyl chain and, subsequently, the film thickness was varied. In agreement with the expectations, the obtained effective MFPs for the Au 4f photoelectrons and C@sub KLL@ Auger electrons in the PEY acquisition mode exceed the

respective values for the elastically scattered electrons of the same kinetic energies (the Au 4f and C@sub KLL@ electrons made up the elastic component of the acquired PEY signals). Furthermore, the PEY-MFP for the C@sub KLL@ Auger electrons increased with decreasing retarding voltage of the PEY detector, which correlates with the increasing contribution of the inelastically scattered electrons in the acquired signal. The obtained results are of importance for the analysis of NEXAFS spectra in both self-assembled monolayers and polymers. This work has been supported by the German Bundesministerium fuer Bildung, Wissenschaft und Technologie through grant No. 05 SF8VHA 1 and by the Fonds der Chemischen Industrie.

11:20am SS2+NS+BI+EL-TuM10 Growth Process and Thermal Stability of Semifluorinated Alkanethiol Self-Assembled Monolayers on Au(111), *M. Hara*, Frontier Research System, RIKEN, Japan; *A. Suzuki*, Tokyo Institute of Technology, Japan; *K. Tamada*, National Institute of Materials and Chemistry, Japan; *H. Fukushima*, Seiko Epson Co., Japan; *T.R. Lee*, University of Houston

Growth process and thermal stability of semifluorinated alkanethiol (CF@sub 3@(CF@sub 2@)@sub m@(CH@sub 2@)@sub n@SH) selfassembled monolayers (SAMs) on Au(111) have been investigated by thermal desorption spectroscopy (TDS) and scanning tunneling microscopy (STM). The growth kinetics showed nearly the Langmuir adsorption isotherm and the etch pits were formed in the upright phase, while the striped phases were not observed in the initial growth stage for shorter (CH@sub 2@)@sub n@ semifluorinated SAMs. In TDS, no significant peaks can be obtained for dimer molecules and decomposed species, suggesting no associative desorption nor dimerization and thermal stability of the semifluorinated molecules during heating up to 650 K. Since longer (CH@sub 2@)@sub n@ semifluorinated SAMs remained the same chemisorbed state in the monolayer after annealing at around 480 K, it has been confirmed that also the alkyl chain part plays an important role for the thermal stability and the ordering in the semifluorinated alkanethiol SAMs. Following those results, we propose more detailed surface phase transition model of semifluorinated alkanethiol SAMs in the growth and annealing processes.

11:40am SS2+NS+BI+EL-TuM11 Multi-technique Study of Self-Assembled AuCN Monolayers on Au(111) Formed by Electrochemical Deposition, T. Yamada, Waseda University, Japan; R. Sekine, Shizuoka University, Japan; T. Sawaguchi, AIST/MITI, Japan

Two kinds of monolayers of AuCN electrodeposited on Au(111), indexed (1.15x@sr@3R-30°) and (1.41x2@sr@3R-30°). have been investigated by XPS, UPS and HREELS as well as LEED, AES and STM to determine the geometrical, electronic and vibrational properties. Electrodeposition was performed in an aqueous 1 mM KAu(CN)@sub 2@ solution by applying an electrode potential about 0 - +0.1 V vs SCE on the Au(111) crystal. Sharp LEED patterns were obtained for these two kinds of adlayers. AES indicated that both of these adlayers were composed Au, C and N without impurity. Well ordered adlattices composing domain structures (domain size ca. 10 nm) were observed by STM. XPS yielded Au 4f signals from AuCN indicating small fractional positive charges on the Au atom incorporated in AuCN. The UPS of AuCN/Au(111) was composed of the Au orbitals and weak signals from CN orbitals, assigned by relativistic DV-Xa molecular orbital calculation. The binding energies of CN orbitals are in the order of 4@sigma@ > 5@sigma@ > 1@pi@, which indicates that the C-Au bond is essentially covalent. HREELS yielded vibrational spectra similar to that obtained for AuCN crystalline powder.@footnote 1@ The C-N stretching frequencies were found to be 2140-2160 cm@super -1@, which are consistent with the covalent nature of the C-Au bond. In the frequency region below 300 cm@super -1@, loss peaks related to the Au-N bonds were seen. The (1.15x@sr@3R-30°) adlayer is concluded to be composed of -AuCN- linear chains (polymer chains) that are identical to those embedded in the AuCN crystal. For the (1.41x2@sr@3R-30°) adlayer, HREELS indicated distortion or breaking of Au-N bonds. Some structural models are proposed for this. These results reveal a special inorganic polymeric feature of the self-assembled AuCN adlayers lying parallel along the surface. @FootnoteText@ @footnote 1@G. A. Bowmaker, B. J. Kennedy and J. C. Reid, Inorg. Chem. 37, 3968 (1998).

Biomaterial Interfaces

Room 202 - Session BI+EL-TuA

Cell-Surface Interactions

Moderator: D.W. Grainger, Colorado State University

2:00pm BI+EL-TuA1 Model Surfaces for Studying and Controlling the Adhesion of Cells, M. Mrksich, The University of Chicago INVITED This presentation will give an overview of the use of self-assembled monolayers of alkanethiolates on gold as model substrates for studying and controlling the interactions of cells with non-natural materials. This surface chemistry approach begins with monolayers terminated in short oligomers of the ethylene glycol group, because these films are inert to the nonspecific adsorption of protein. Monolayers patterned into regions presenting glycol groups with the complementary regions presenting hydrophobic surfaces are excellent substrates for patterning the attachment of cells. The immobilization of ligands to these inert films gives substrates to which proteins can selectively bind, but which otherwise rule out non-specific interactions of proteins. This approach can be extended to give substrates that mediate the attachment of mammalian cells. Monolayers presenting the peptide Arg-Gly-Asp (a ligand for cell-surface integrin receptors) mediate the selective attachment and spreading of fibroblast cells. This presentation will also discuss the design of dynamic substrates that can alter, in real time, the presentation of ligands to an attached cell and hence influence the behaviors of adherent cells. These active substrates are based on electroactive monolayers that present redox-active groups which can be switched by applying electrical potentials to the underlying gold. A first example uses substrates that can be switched to turn on the immobilization of ligands. This strategy has been used to switch regions of the substrate from an inert state to a state that permits the adhesion and migration of cells. A second example uses substrates that can selectively release immobilized ligands from the monolayer. These examples establish that self-assembled monolayers of alkanethiolates on gold are an excellent model system for controlling the adhesion of cells and will find wide use both in fundamental studies for biology and in applied targets for biotechnology.

2:40pm BI+EL-TuA3 Cell Respone to Chemically and Topographically Modified Surfaces, D.S. Sutherland, A.S. Andersson, K. Glasmastar, S. Petronis, Chalmers University of Technology, Sweden; F. Backhed, A. Richter-Dahlfors, Karolinska Institute, Sweden; U. Lidberg, University of Gothenburg, Sweden; B. Kasemo, Chalmers University of Technology, Sweden

The properties of surfaces have long been known to influence cellular behaviour. Both the chemistry and topography of surfaces have been shown to effect different aspects of cellular response. With the advent of micro and nanofabrication it is now possibl e to study these interaction in a more detailed fashion, isolating specific surface structures and systematically varying their size and shape. In a parallel multicentre project a range of micro and nanofabricated surfaces are used in cell culture experi ments with a range of cell types. The specific surface designs were selected to give chemical and topographic cues on a range of length scales from the micron and submicron to the nanometre and were used as a set, to screen for the influence of surface st ructure on cellular behaviour. Similar sets of well-characterised surfaces were used in a number of different cell culture systems, including epithelial, endothelial, mammary gland and pancreatic cells, to look for both cell-specific interactions and g ene ric correlations. The studies have taken advantage of recent advances in microbiological techniques, focussing on different aspects of gene expression, cell differentiation and cell-cell signalling as well as more traditional adhesion, proliferation and m orphologic analysis. Examples of preliminary results obtained so far include: 1. Non-adherence/proliferation of three cell types to lipid bilayers (so called supported membranes) 2. Expression of a specific cytokine by epithelial cells is influenced by the microtopography of the surface. Additional results from ongoing studies are expected within a few months.

3:00pm BI+EL-TuA4 Directing Endothelial Cell Attachment and Growth Using a Novel Ozone Patterning Technique, S.R. Webb, T. Boland, Clemson University

Being able to modify surfaces to control cellular behavior, i.e. adhesion, spreading, migration, and or proliferation is extremely important in the development of materials for tissue engineering applications. Of particular interest in the field of vascular research are surfaces that will direct cell attachment and growth in the presence of RGD containing serum proteins, which may adsorb to the material surface. In this study, cell response to

patterned materials was examined by employing highly organized monolayers of self-assembled (SAM) octadecytrichlorosilane (OTS) on silicon oxide wafers. OTS surfaces were exposed to ozone for a varying amount of time ranging from 1-4 minutes. The remaining surfaces were exposed to ozone via a micron size mask, allowing only the exposed areas to be etched. The surfaces were analyzed by ellipsometry and electron spectroscopy for chemical analysis (ESCA). Bovine aortic endothelial cells (BAEC): were cultured in MEM + 10% Fetal Bovine Serum + 1% antibiotic solution. Cells were seeded and cultured in 96 well plates in the presence of pure and patterned OTS surfaces. Cell attachment and growth of endothelial cells on pure OTS monolayers was very poor, most likely because of the denaturing of serum proteins near the surfaces. The surfaces exposed to ozone showed varying film thickness depending on the dose, and a strong carbonyl peak in the ESCA spectra, indicating the presence of an oxidized thin organic film. Cell attachment to etched surfaces and growth exceeded the control tissue culture polystyrene. Cell density increased in regions of the pattern to a confluent layer. The cell spreading and attachment on the micro-patterned surfaces suggests that the cells may be able to attach more firmly to the extracellular proteins on the patterned surfaces. The result from this cell growth study will aid in designing micro-patterned surfaces varies areas, such as, cell-based biosensors, biocomputers, and new biomaterials.

3:20pm BI+EL-TuA5 Cellular Interactions with Self-assembled Monolayers, G.J. Leggett, University of Manchester Institute of Science and Technology, UK INVITED

The development of a detailed understanding of the influence of surface chemical structure on mammalian cell attachment has been confronted with difficulties. Not only are the biological problems inherently complex, but until recently there have not been adequately well defined model surfaces for fundamental studies. The advent of self-assembled monolayers (SAMs) has promised to transform this situation, by providing well-defined surfaces with structures and chemistries that may readily be controlled, and the past five years have seen growing interest in the use of SAMs to model cellular interactions with artificial substrata. In the present work, SAMs with a range of alkyl chain lengths and terminal groups have been used in studies of the attachment of murine 3T3 fibroblasts and primary human osteoblast-like cells. The sensitivity of cellular attachment to subtle changes in adsorbate molecular structure and order has been explored. The responses of cells to micropatterned substrata formed using photopatterning methods have been explored. The organisation of structural elements, including filamentous actin organisation and focal contact formation, within the cell cytoskeleton has been explored using immunochemical methods. The effect of protein adsorption has been probed by comparing attachment from serum-free and full media, and by pre-exposing surfaces to protein solutions. Valuable insights have been gathered into the relationship between surface chemical structure and cellular behaviour.

4:00pm BI+EL-TuA7 Artificial Networks of Rat Hippocampal Neurons on Microelectrode Arrays, C.D. James, A.J. Spence, Cornell University; N. Dowell, Wadsworth Center/Department of Health; H.G. Craighead, M.S. Isaacson, Cornell University; J. Turner, W. Shain, Wadsworth Center/Department of Health

The construction of artificial neuronal networks from dissociated primary neurons will permit study of synaptogenesis, synaptic plasticity, and neuronal processing. However, a thorough investigation of these processes requires two important components: a flexible method of producing patterned cell networks, and long-term (weeks) studies of such cell networks. To address these issues, microelectrode arrays have been fabricated to conduct long-term, non-invasive extracellular measurements of spontaneous and induced action potentials. In addition, we have used two methods, microcontact printing and conventional photolithography, to align patterns of molecules, such as poly-L-lysine and laminin, to the microelectrode arrays. Surface analysis of the patterned molecules was completed to assess the relevant factors for successfully promoting cell attachment and neurite guidance. Issues dealing with the reliability and stability of the microfabricated electrode arrays, specifically for primary neuron cell cultures, will also be addressed.

4:20pm BI+EL-TuA8 Living Neural Cells as Components in Sensors and Computational Devices, J.J. Hickman, Clemson University INVITED We are developing the methodology to build hybrid biological/nonbiological systems to create new information technology devices. This presentation will focus, from a bioengineering standpoint, the steps necessary to build such a device and some of the possible functions of

these devices. We are using self-assembled monolayers (SAMs) to control the intrinsic and geometric properties of surfaces in contact with biological systems. The use of surface modification techniques allows us to tailor the interface between biological/nonbiological materials independent of the bulk composition of the nonbiological material. The ability to control the surface composition of the in vitro system as well as controlling other variables, such as growth media and cell preparation, all play important roles in creating a defined system for devise operation. This defined system has been used as a test-bed to evaluate surface coatings for neuronal interactions with electronic materials. We have used the geometric control of the surface composition afforded us by SAMs to create in vitro circuits of mammalian neurons. We have also recorded the electrophysiological signals produced by neurons on the patterned SAMs in response to stimuli. The surfaces have been characterized by X-ray photoelectron spectroscopy (XPS), imaging XPS and contact angle measurements and we have related the intrinsic properties of the surface and the proteins deposited by the cells to cellular development. We are using what we learn for a more fundamental understanding of cellular development and also to create sensors using living neurons as the sensor element. The continuing development of this technology will be discussed, our latest results, as well as the implications and applications for (a) biosensor fabrication, (b) neuronal circuit design, and (c) biological computation.

5:00pm BI+EL-TuA10 Tissue Formation of Hepatocytes on Micro-Porous Films of Polylactide, T. Nishikawa, RIKEN, Japan; K. Nishikawa, R. Ookura, J. Nishida, S.-I. Nishimura, H. Ookubo, H. Kamachi, M. Matsushita, S. Todo, Hokkaido University, Japan; M. Shimomura, RIKEN, Japan

Control of interaction between cells and material surfaces has been considered as a fundamental issue in designing and developing biomaterials for various purposes such as cell culture, implantation, and tissue regeneration. Surface morphology is one of the factors which can control the interaction. We previously reported that two-dimensional regular honeycomb pattern appear as a surface morphology of polymer films which were fabricated by casting dilute solution of amphiphilic polymers on solid substrates in a humid atmosphere. Recently we found that the honeycomb morphology can be applied to micro-patterning of cell culture substrates and that rat hepatocytes recognize the micro-patterned surfaces from chemical and morphological aspects and change their morphology and functions. Here we show that self-supported honeycomb films can be fabricated by casting a dilute solution containing polylactide (PLLA) as major component of the films and amphiphilic polymer as component for induction of honeycomb morphology. The honeycomb films worked as cell culture substrates for rat hepatocytes. Hepatocytes on the honeycomb films formed a colony, which exhibited tissue-like structure and express high level of albumin secretion, which was comparable to that of spheroids of hepatocytes. The tissue formation of hepatocytes specifically occurred on the honeycomb films of PLLA, but not on flat films of PLLA. The colony of hepatocytes kept the morphological features and liver specific function at day 14. This indicates that micro-porous films of PLLA would be appropriate for long term culturing of hepatocytes. Recently we succeeded in culturing hepatocytes on both sides of the self-supported honeycomb films of PLLA. In this sense, we believe that our materials possessing regular micro-pores are applicable to artificial extra-cellular matrices for tissue engineering.

Electronics

Room 312 - Session EL+NS-TuA

Nanoelectronics

Moderator: R.S. Goldman, University of Michigan

2:00pm EL+NS-TuA1 Nano-switches Using Vacuum Nano-electronics and Superconducting Weak Links, D.G. Hasko, Cambridge University, UK INVITED

New physical principles influence device operation when size is reduced to the nanometre range Recent research has lead to two types of switching devices; vacuum nanoelectronic (VNE) and superconducting switches have been described and are reviewed in this paper. Conventional vacuum microelectronics exploits cold field emission of electrons in devices made by microcircuit fabrication techniques but requires UHV vacuum operating conditions. By reducing the field emission tip radius and the tip-extractor electrode spacing a new class of VNE devices may be operated at lower voltages and with improved stability. Tips of nanometre size also show much smaller angular spreads and reduced energy spread. Diode and triode devices, with electron transport path length of ~100nm (shorter

than the mean free path in air) were fabricated and their electrical characteristics reported. Hot phonon injection from an electrically isolated heater has demonstrated effective switching behaviour in Nb weak link junctions and is of great interest for high speed and quantum effect circuit functions. This method isolates the control circuit from the weak link and has demonstrated significant device gain in contrast to previous device structures.

2:40pm EL+NS-TuA3 Persistent-current Qubits for Quantum Computation, E.L. Mooij, DIMES Institute, The Netherlands INVITED

In a collaboration between MIT and Delft University we have designed a quantum bit (qubit) for quantum computation that consists of a superconducting loop with three small Josephson junctions in series.@footnote 1@ When the flux through the loop is close to half a superconducting flux quantum, the qubit has two stable macroscopic quantum states with persistent currents in opposite directions. Quantum transitions between the two states are possible if the capacitance of the junctions is small. Samples are fabricated from aluminum and measurements are performed at very low temperatures to reduce decoherence effects. First measurement results have been obtained that demonstrate the quantum superposition of the states. Next experiments will focus on time-dependent response. With these qubits in principle a scalable quantum computer can be constructed if the decoherence time is long enough. A quantum computer of sufficient size can perform calculations beyond the power of a conventional computer. However, many challenges will have to be faced before a quantum computer is realized. @FootnoteText@ @footnote 1@J.E. Mooij, T.P. Orlando, L.Levitov, Lin Tian, Caspar H. van der Wal and Seth Lloyd, Science 285, 1036 (1999)

3:20pm EL+NS-TuA5 Coulomb Blockade Devices Fabricated by AFMmanipulation of Nanoparticles, S. Carlsson, T. Junno, H. Xu, L. Samuelson, Lund University, Sweden

We report successful fabrication of Coulomb blockade devices obtained by manipulation of pre-fabricated nanoparticles, using an atomic force microscope (AFM) as a nano-engineering tool. This approach, together with in-situ electrical measurements during manipulation, allows the formation of tunnel gaps with accuracy on the Ångstrom scale. Three-terminal singleelectron transistors (SETs) with ideal electrical characteristics are obtained, demonstrating Coulomb blockade as well as Coulomb staircase in the I-V characteristics, and with hundreds of current oscillations as function of gate voltage. Furthermore, we have built double-island structures with three gaps trimmed to tunneling dimensions and with two addressing gates, allowing control of the charge distribution, or polarization, of these two-atom artificial molecule objects.

3:40pm EL+NS-TuA6 A Novel Scheme for the Fabrication of Ultra-short Metal-oxide-semiconductor Field-effect Transistors, *R. Martel*, IBM T.J. Watson Research Center; *J. Appenzeller, J. Knoch*, Physikalisches Institut, RWTH Aachen, Germany; *K. Chan*, IBM T.J. Watson Research Center; *M. Tanner, S. Thomas, K.L. Wang*, University of California, Los Angeles; *Ph. Avouris*, IBM T.J. Watson Research Center; *J.A. del Alamo*, Massachusetts Institute of Technology; *P. Solomon*, IBM T.J. Watson Research Center

We present a novel scheme for the fabrication of ultra-short channel length metal-oxide-semiconductor field-effect transistors (MOSFETs) involving nanolithography (proximal probe or e-beam) and molecular beam epitaxy (MBE). The active channel is undoped and is defined by a combination of nanometer-scale patterning and anisotropic etching of a n@super ++@-layer grown on a silicon on insulator (SOI) wafer. The method is self-limiting and can produce MOSFET devices with channel lengths of less than 10nm. Measurements on the first batches of n-MOSFET devices fabricated with this new approach will be presented. They show very good output characteristics and good control of the short channel effects. The combination of highly doped contact areas (n@super ++@ 1x10@super 20@cm@super -3@) with a nominally undoped channel region (p@super -@ 5x10@super 14@cm@super -3@) is now being explored further to keep the parasitic resistances low and possibly achieve ballistic transport at room temperature.

4:00pm EL+NS-TuA7 Quantitative Analysis of Charge Injection and Discharging of Si Nanocrystals and Arrays by Electrostatic Force Microscopy, L.D. Bell, Jet Propulsion Laboratory, Caltech; E. Boer, M. Ostraat, Caltech; M.L. Brongersma, Caltech, US; R.C. Flagan, H.A. Atwater, Caltech

Charge injection and storage in dense arrays of silicon nanocrystals in SiO@sub 2@ is a critical aspect of the performance of potential nanocrystal

Tuesday Afternoon, October 3, 2000

flash memory structures. We have performed charging experiments on Si nanocrystals both embedded within and deposited on SiO@sub 2@ using conducting-tip atomic force microscopy (AFM). In the case of both isolated aerosol-deposited nanocrystals and those formed by ion implantation and annealing of SiO@sub 2@ films, charging has been accomplished by moving a conducting AFM tip close enough to the nanocrystal to transfer charge. This charging and subsequent discharging were characterized by monitoring the apparent change in nanocrystal height detected by AFM. The trapped charge produces an electrostatic force component that changes the response of the AFM tip, causing a change in the apparent height of the nanocrystal. This mode of electrostatic force microscopy (EFM) together with electrostatic modeling enables quantitative measurement of the trapped charge and discharging dynamics. Simulation enables the EFM sensitivity to be estimated systematically as functions of tip radius and height. Forces due to interaction with this charge and the induced charge on the tip can be determined, and AFM response to these forces can be calculated. Constant-force-gradient contours have been calculated that agree well with measured profiles, and we can determine the amount and location of the injected charge as well as some details of the discharge mechanism. Trapped charge as small 7e is detected in isolated small nanocrystals, and charge in the range 100e - 1000e is observed in larger isolated nanocrystals or embedded nanocrystal ensembles. The combination of EFM imaging and simulations can be used to estimate the homogeneity of the charge density and to probe for high conductance paths within a nanocrystal floating gate. Modeling indicates a discharge mechanism consistent with tunneling through a field-lowered barrier.

4:20pm EL+NS-TuA8 Quantized Conductance in AuPd Alloy Nanocontacts, A. Sakai, A. Enomoto, J. Sasaki, S. Kurokawa, Kyoto University, Japan

Quantization of conductance can be observed most beautifully in Au nanocontacts but much less clearly in transition metals such as Pd. Then, an interesting problem is how the quantized conductance changes by alloying Au with Pd. Do all quantized peaks in the conductance histogram of Au disappear by a small amount of Pd, or do they survive even for Pdrich nanocontacts? To answer this problem, we have carried out conductance measurements on AuPd nanocontacts in air at room temperature. We prepared Au@sub 1-x@Pd@sub x@ alloy wires with x = 20, 40, 50, 80, and 95 wt%, and measured the transient conductance at the break of two contacting wires. We find that the transition from the conductance behavior of Au to that of Pd takes place gradually with increasing the Pd concentration: sharp peaks in the histogram of Au are suppressed and replaced by a broad and featureless distribution observed in the histogram of Pd. At x = 40 and 50 wt%, both quantized peaks of Au and broad background of Pd coexist in a conductance histogram. This result implies that the conductance of AuPd nanocontacts becomes that of Au or Pd depending on which one of two constituent atoms occupies the narrowest constriction of the contact.

4:40pm EL+NS-TuA9 Bistability in Conductance of Point Contact formed between a Metal Tip and Ga-terminated Si(111), *S.L. Pryadkin*, *D. Chen*, Rowland Institute for Science

Recently, it has been found that voltage-current dependence of a tunnel junction formed by an STM tip and a Ga terminated Si(111) surface exhibits large hysteresis at 77K, similar to that of a double barrier structure.@footnote 1@ This new finding raises the possibility of creating nanoscale storage and switching devices, compatible with silicon technology. To further explore this potential, we have studied the effects of temperature and dopping. It is found that the hystersis exists in a wide range of temperature. Moreover, when the tip is brought to a point contact with the surface, it still gives rise to the bistable transport. This allows us to simplify the junction structure even further and to determine the timing characteristics of this new nanoscale switching/storage device. @FootnoteText@@footnote 1@ I.B.Altfeder, D.M.Chen Phys.Rev.Lett. 84, p.1284(2000).

5:00pm EL+NS-TuA10 Analysis of Non-linear Behaviour in Gold Nanowires, A. Wlasenko, P. Gruetter, McGill University, Canada

In the presented experiment, a gold nanowire is formed with a mechanical break junction. A voltage bias is applied in the form of a triangle wave (typically 0.1 Hz, 2V@sub pp@) plus a small sine wave (typically 10kHz, 10mV@sub rms@) across the nanowire in series with a load resistor. A current pre-amp measures I(V), while a lock-in amplifier measures its partial derivative with respect to voltage. While others have made I(V) measurements of nanowires (Costa-Kramer et al., PRB 55, 5416 (1997) and Costa-Kramer et al., Nanoscale Science and Technology pp. 1-10 (1998)

Kluwer Acedemic), the simultaneous measurement of the derivative allows powerful analysis without choosing a physical model or using mathematical fits. In general, the current is not just a function of voltage [I(X,V)=g(X)f(X,V)]. For instance, the geometry of the nanowire or presence of scatterers should have an effect on the current. The analysis indicates how changes in these non-voltage factors [X] are changing the current [@DELTA@I(@DELTA@X,V)] without having to know explicitly what these are factors are or how they are changing. It is also possible to determine how the form of current f(X,V) is changing with respect to the voltage without knowing g(X). Several individual sets of data shall be investigated that illustrate particular features of both typical and atypical nanowire behaviour. A discussion is presented of the possible physical arguments concerning these features and general trends.

Semiconductors

Room 306 - Session SC+EL+OF-TuA

Organic Chemistry on Semiconductor Surfaces Moderator: J.E. Crowell, University of California, San Diego

2:00pm SC+EL+OF-TuA1 Novel Reactions of Organic Molecules for Controlled Modification of Semiconductor Surfaces, D.J. Doren, University of Delaware INVITED

Recent theoretical work on reactions of organic molecules with semiconductor surfaces will be described. The focus will be on several mechanisms that allow molecules to react with low activation barriers on (100) surfaces of Si, Ge and diamond. Cycloaddition reactions are the most thoroughly understood reactions of organic molecules on these surfaces, having been studied extensively by both theory and experiment. This work has established several families of molecules that readily chemisorb. However, in several cases, there are competing side reactions. The origins of this competition, and some approaches to controlling selectivity tbrough the choice of precursor molecule, will be discussed. Finally, a reaction that attaches an organic molecule to the surface by dissociation (as opposed to cycloaddition) will be described.

2:40pm SC+EL+OF-TuA3 Peter Mark Memorial Award Address, S.F. Bent¹, Stanford University INVITED

Tailoring the surface properties of semiconductor materials through organic modification is one means of providing new functionality to the semiconductor surface, incorporating properties such as passivation, lubrication, optical response, molecular recognition, or biocompatibility. Chemical modification also has tremendous utility for the controlled synthesis of organic/semiconductor interfaces for numerous electronic and optical applications, including the coupling of organic-based devices to silicon-based microchip technology. In this presentation, I will discuss different organic attachment strategies used to functionalize semiconductor surfaces in a dry processing environment. Unsaturated molecules, such as alkenes or dienes, can be attached by cycloaddition reaction across the Si-Si dimer at the Si(100)-2x1 surface; the reaction occurs at the surfaces of Ge and diamond, as well. Amine groups provide another reactive functionality for surface attachment. The relative reactivities of cycloaddition, N-H bond dissociation, and nitrogen lone pair interactions at the Si(100)-2x1 surface will be described using a series of pyrrole compounds. The use of protecting groups to manipulate the surface reaction pathway will be demonstrated. The potential for these different classes of attachment reactions to impact future applications will also be discussed.

3:20pm SC+EL+OF-TuA5 Structure of Cyclopentene Adsorbed on InP (001)-(2x1) Surface, Q. Fu, C.H. Li, D.C. Law, M.J. Begarney, R.F. Hicks, University of California, Los Angeles

It has been a growing interest in engineering ordered, defect free organic thin films on semiconductor substrates for the next generation miniature electronic devices. Using metalorganic vapor phase epitaxy, we have successfully grown indium phosphide (2x1) surface terminated with a complete layer of phosphorous dimers. On InP (2x1) surface, a dangling bond on each phosphorous dimer is filled with a single electron, which makes it an ideal substrate for growing organic films through reactions with @pi@-bond of unsaturated molecules. Here, we have characterized the molecular structure of cyclopentene adsorbed on the InP (2x1) surface by scanning tunneling microscopy, and molecular cluster calculations. It is

¹ Peter Mark Memorial Award Winner

found that the exposed phosphorous dimers are the adsorption sites for the unsaturated organic molecule. Two adsorption configurations were identified: one with the C@sub 5@H@sub 8@ molecule sitting on top of a P dimer, and another one with the C@sub 5@H@sub 8@ molecule bridging across two neighboring P dimers. At the meeting, we will present a comparison of cyclopentene adsorption characteristics on InP (001)-(2x1) versus Si (100)-(2x1).

3:40pm SC+EL+OF-TuA6 Formation and Reaction of Organic Layers on Germanium: Reaction of 1,5-cyclooctadiene with the Ge(100) Surface, P. Prayongpan, D.S. Stripe, C.M. Greenlief, University of Missouri, Columbia

Organic alkenes can bond to Ge(100) surfaces to produce monolayer organic films that are chemically homogeneous and structurally ordered. The bonding of these molecules to the Ge(100)-(2x1) reconstructed surface is analogous to a class of ring-forming reactions known in organic chemistry as [2+2] cycloaddition reactions. While the bulk reactions involve the reaction of two alkene groups to form a four-member ring, the analogous surface reaction involves two electrons from the organic alkene and two electrons from the surface Ge=Ge dimers. Here, the formation of ordered organic layers on Ge(100) substrates is examined by the reaction of 1,5-cycloocatadiene with Ge(100). This molecule reacts with the Ge dimers leading to a [2+2] cycloaddition reaction product. A combination of ab initio calculations and surface sensitive experimental techniques are used to probe the interactions. Surface modification of the organic layers is also explored. The reaction of the organic layers with atomic hydrogen and a series of alcohols will be discussed.

4:00pm SC+EL+OF-TuA7 A Comparative Study of the Bonding of N-Containing Heterocyclic Molecules to the Si(001) Surface, X. Cao, S.K. Coulter, H. Liu, J. Liu, R.J. Hamers, University of Wisconsin, Madison

Recent studies of a variety of unsaturated hydrocarbons has lead to increased interest in understanding the factors controlling bonding of more complex organic molecules to silicon surfaces. By understanding the propensity for heterocyclic molecules to bond into various possible configurations, we are able to gain insight into the factors controlling selectivity in molecule-surface bonding. We have studied the adsorption of pyrrole and its partially-unsaturated analog, 3-pyrroline, onto the Si(001)-(2x1) surface using Fourier-transform infrared spectroscopy, X-ray photoelectron spectroscopy, and scanning tunneling microscopy (STM). At 300 K, XPS spectra of pyrrole show a single, sharp N(1s) level, while FTIR spectra show that the molecule retains the high-frequency peaks that are characteristic of aromatic molecules; isotropic labeling studies show that attachment occurs through the N atom via cleavage of the N-H bond. These results show that pyrrole retains its aromatic character after bonding to the surface. In contrast, XPS and FTIR data for 3-pyrolline shows that it can bond through the N atoms or through its C=C bond via the surface equivalent of a [2+2] cycloaddition reaction. This study shows that molecules with aromatic rings show a strong preference for retention of this aromaticity, while molecules without aromaticity have more diverse chemical bonding configurations. Implications for understanding the attachment of other N-containing molecules to surfaces will be discussed.

4:20pm SC+EL+OF-TuA8 Reaction of Pyrrole and Pyrrole Derivatives on Si(100)-2x1, G.T. Wang, C. Mui, C.B. Musgrave, S.F. Bent, Stanford University

The ability to covalently bond to semiconductor surfaces organic layers with custom-tailored functionality could have applications in a number of areas, including lithography, molecular electronics, sensors, and low k dielectric materials. Previous studies have shown that the Si(100)-2x1 surface dimer can react with unsaturated hydrocarbons, forming covalently bound [4+2] Diels-Alder and [2+2] cycloaddition products at the surface. Amines have shown promise as alternative candidates for layer-by-layer growth and the model amine ammonia is known to react with silicon via N-H dissociation across the surface dimer. The use of more complex amines for surface modification requires an understanding of how various functional groups in the amine affect its reactivity and bonding configuration with the surface. In this study, the interaction of pyrrole and pyrrole derivatives, including saturated and unsaturated secondary and tertiary amines, with the Si(100)-2x1 surface under ultra-high vacuum is investigated via multiple internal reflection infrared spectroscopy. Auger electron spectroscopy, temperature programmed desorption studies, and ab initio quantum chemistry calculations. The results show that the nitrogen lone pair plays an important role in the reaction of amines with the Si(100) surface. In particular, the stable room temperature molecular adsorption of methylpyrrolidine through its lone pair is permitted due to the presence of a protecting methyl group, while its unprotected analogue,

pyrrolidine, proceeds to covalently bond to the surface through N-H dissociation. Additionally, results examining the reaction of the Si(100) surface with a model amide (N-methylacetamide), which contains both carbonyl and amine functionalities through a peptide unit and hence could serve as a bifunctional unit for layer-by-layer growth, are presented.

4:40pm SC+EL+OF-TuA9 Attaching Aromatic Molecules to the Si(001) Surface via Oxygen and Sulfur Tethers, S.K. Coulter, M.P. Schwartz, J. Liu, R.J. Hamers, University of Wisconsin, Madison

Phenol, benzenethiol and phenyl disulfide have been used as model systems to compare the bonding of chemically-similar aromatic molecules to the Si(001)-2x1 surface through different Group VI tethers. The behavior of these substituted aromatic hydrocarbons on the Si(001) surface has been investigated using Fourier transform Infrared Spectroscopy (FTIR), X-ray Photoelectron Spectroscopy (XPS) and Scanning Tunneling Microscopy (STM). Both FTIR and XPS indicate that phenyl disulfide bonds exclusively through the sulfur substituent groups. Phenol and benzenethiol molecules bond predominately through their oxygen/sulfur substituent groups, although a small minority may chemisorb on the surface via ring attachment. Thermal studies indicate that the molecules attached to the surface via sulfur or oxygen tethers are stable to temperatures above 550 K. STM studies show that these molecules attach directly to the silicon dimer and, in the case of phenyl disulfide, form ordered rows of aromatic rings.

5:00pm SC+EL+OF-TuA10 Chemical Reactions on the Diamond(100) Surface: First-principles Theory and Comparisons to Experiment, D.R. Fitzgerald, D.J. Doren, University of Delaware

Density functional theory calculations have been used to investigate the structures, energetics, and reaction pathways of the [4+2] and [2+2] cycloaddition reactions of butadiene with the C(100)-2x1 surface. Onedimer and three-dimer cluster models were used to represent the surface. Vibrational spectra of the product species were also calculated. Activation free energies suggest that the [4+2], or Diels-Alder mechanism, will be kinetically favored. The presence of adjacent unreacted surface dimers affects the orientation of the cycloaddition product. The adsorption of hydrogen on the surface has also been studied. Cluster size is seen to have a large effect on the vibrational spectrum of the adsorbed hydrogen. Theoretical results are compared to recent experiments.

Tuesday Evening Poster Sessions, October 3, 2000

Electronics

Room Exhibit Hall C & D - Session EL-TuP

Poster Session

EL-TuP1 Polarization Effect on Copper Electroplating in Presence of Thiourea Additives, C.-L. Cheng, Y.-S. Lin, Chung-Yuan University, Taiwan Copper metallization will play an important role in future microelectronic processing because Cu has lower resistivity and higher electromigration resistance compared to Al. Copper could be deposited by either physical sputtering, chemical vapor deposition (CVD), or electrochemical deposition. Since electroplating has advantages of low processing temperature, short processing time, and simple deposition facilities, which compared to traditional sputtering and CVD, electroplating becomes the most attractive techniques implemented in Cu metallization. Polarization becomes very important in Cu electroplating because it could effect formation of copper grain and copper filling mechanism. One common method to change the degree of polarization is using chemical additives during electroplating. In order to realize polarization effect on copper formation during electroplating, we choose a series of thiourea additives: thiourea, Nacetylthiourea, and N.N-diethylthiourea used as chemical additives on copper electroplating. Since N,N-diethylthiourea has a pair of electronpushing groups (di-ethyl groups), it could enhance electron density around sulfur atom to increase interaction with copper ions and make polarization higher. The results are shown polarization will become higher when N,Ndiethylthiourea is present and lower when N-acetylthiourea (electron puller) is existed. The finer grain size of copper forms when the higher polarization appears. Based on this study, we demonstrate that N,Ndiethylthiourea could be used to act as gap filling promoters without void formation in the 0.25 micrometer dimension of trench with an aspect ratio of 4

EL-TuP2 Low Temperature, Single-Source CVD of ZrB2 and HfB2 Films as Cu Diffusion Barriers and Interconnects in Next-Generation ULSI, J.H. Sung, D.M. Goedde, G.S. Girolami, J.R. Abelson, University of Illinois at Urbana-Champaign

Thin films of the metallic ceramics ZrB@sub 2@ and HfB@sub 2@ have high electrical conductivity and are very effective diffusion barriers against copper; hence, they are attractive as interconnect and barrier materials for next-generation ULSI technology. Previously, we deposited highly conformal (~ 100 % bottom coverage) ZrB@sub 2@ and HfB@sub 2@ films using Zr(BH@sub 4@)@sub 4@ and Hf(BH@sub 4@)@sub 4@ singlesource precursors in a CVD reactor with a remote hydrogen plasma source. The atomic H enhanced the release of excess B from the growth surface at low temperature, producing stoichiometric films with excellent properties. The film structure could be controllably varied from amorphous to polycrystalline by varying the substrate temperature from 250 - 800 °C, while maintaining stoichimetry. Here, we demonstrate that a single layer of ZrB@sub 2@ or HfB@sub 2@ can successfully replace the complex W/TiN/TiSi@sub 2@ multilayer that is currently used for ULSI metallization of Si. To achieve low contact resistivity on p-type Si, we adjust the ZrB@sub 2@ or HfB@sub 2@ stoichiometry during the initial deposition in order to provide a controlled source of excess B atoms. This is done by briefly reducing the remote hydrogen plasma power, which increases the B content above stoichiometric ratio. We will also present results for ZrB@sub 2@ or HfB@sub 2@ deposited at < 300 °C: electrical resistivity less than 40 µm@ohm@-cm, effective diffusion barrier against Cu during annealing to 700 °C for 1 hour, and low specific contact resistivity.

EL-TuP3 Study of Electrical and Interfacial Properties of CVD-W/n-Si@sub 0.83@Ge@sub 0.17@/Si(001) Schottky Contacts, Y.C. Jang, K.S. Kim, D.O. Shin, Sungkyunkwan University, South Korea; K.-H. Shim, Electronics and Telecommunications Research Institute, South Korea; S. Youn, K. Roh, Y. Roh, N.-E. Lee, Sungkyunkwan University, South Korea, Korea

The formation of metal contacts on Si@sub 1-x@Ge@sub x@ alloys plays an essential role in the various devices utilizing Si@sub 1-x@Ge@sub x@/Si including heterojunction bipolar transistors, and photodetectors. Therefore, interactions between the metals and the Si@sub 1-x@Ge@sub x@ layers are of technical and scientific interests for understanding of Schottky barrier formation. Chemical vapor deposited W as a refractory metal has been commonly used in microelectronics industry and has several characteristics that make it very attractive candidates for contact metallization. The effective Schottky barrier height measurements on the CVD-W/n-Si@sub 1-x@Ge@sub x@(001) system, however, have not reported so far as we know. In this study, we investigated the electrical properties of CVD-W/n-Si@sub 1-x@Ge@sub x@(x=0.17) and CVD-W/n-Si schottky contacts. Fully-strained 90-nm-thick n-type Si@sub 0.83@Ge@sub 0.17@ epitaxial thin film with the P concentration of 5x10@super 17@ cm@super -3@ was deposited on p-type Si(001) substrate at the substrate temperature of 650°C by LPCVD utilizing SiH@sub 4@, GeH@sub 4@, PH@sub 3@, and H@sub 2@ gases. W layers were grown by LPCVD using the WF@sub 6@, SiH@sub 4@, and H@sub 2@ at the growth temperature of 350 - 550°C. W Schottky contacts with various sizes from 0.2 mm@super 2@ to 0.5 mm@super 2@ were defined by photolithography and etching. Electrical properties of the CVD-W/n-Si@sub 0.83@Ge@sub 0.17@ Schottky diodes were characterized by I-V measurements in the forwardbiased direction at room temperature. The measured effective Schottky barriers (@PHI@@sub Bn@) for CVD-W/n-Si@sub 0.83@Ge@sub 0.17@ and CVD-W/n-Si were 0.553 eV and 0.671 eV at the W deposition temperature (450°C). The structural, chemical and interfacial properties of CVD-W/n-Si@sub 1-x@Ge@sub x@(x=0.17) interfaces were analyzed by XRD, TEM, RBS, and AES. The correlation between electrical and structural properties of their interfaces will be discussed.

EL-TuP4 Work Function and Barrier Height Correlation for Al/GaAs Schottky Contacts Modified by Ultra-Thin, Doped Si and Ge Interlayers, *T.A.R. Müller, M.I. Nathan, University of Minnesota; A. Franciosi, University* of Minnesota and Universita' di Trieste; *C.J. Palmstrom,* University of Minnesota

A promising alternative to alloyed contacts to GaAs, which suffer from lateral diffusion and spiking problems, is the deposition of ultra-thin (1eV, while the co-deposition of Si with As shows an increase in the work function of 0.2eV for a Si-coverage of 0.5ML. The corresponding barrier height lies in the 0.2eV range. In this talk, we report a systematic study of the effect of Ge interlayers (

EL-TUP5 Enhancement of Mobility with Double Delta-doped Quantum Wires by Focused Ion Beam, S. Choi, M. Leung, G. Stupian, N. Presser, The Aerospace Corporation; *C. Lee*, Honam University, Korea

100nm wide delta-doped quantum wires were fabricated by the Molecular Beam Epitaxy (MBE) and a subsequent Focused Ion Beam (FIB) milling process. Ion beam focused to submicrometer diameters offers a radical departure from the conventional fabrication routine for quantum wires such as electron beam lithography. First of all,all the double delta-doped AlGaAs/GaAs quantum well structures were grown by solid source MBE system. N-type delta-doping was made in the spacer region close to the well during the MBE growth. The structures grown are a single well with two 100nm AlGaAs spacers. 5 micrometer wide Hall bar mesas were prepared by the optical lithography and a subsequent chemical etching. Next, 100nm wide AlGaAs/GaAs quantum wires were made by a 25KeV focused Gallium ion beam at 10pA current. The excited subbands in the quantum well structures may have significant amount of carrier densities placed in the undoped region where Coulombic scattering is reduced. In addition to the delta-doping effect on the reduction of scattering, one dimensional confinement effect due to 100nm wide wire structures may contribute to the enhancement of mobility along the wire direction. As a result, three times enhancement of mobility compared to the quantum well structures were found in the low temperature Hall measurements with double delta-doped quantum wires. This type of structures and a fabrication technique may show great promise for obtaining high mobility with high densities for semiconductor devices.

EL-TuP6 Implantation of AIAs Etch-Stop Layers by MBE for Recessed Gate P-HEMTs, G. Zhou, W. Liu, M. Lin, Alpha Industries, Inc.

The AlGaAs/InGaAs/GaAs pseudomorphic high electron mobility transistor (p-HEMT) has been widely accepted for many high-performance, low cost millimeter-wave applications and high-speed digital circuits. In HEMTs fabrication process, one of the most critical steps is gate recess etching. This is because recess groove profiles have significant influences on the DC and RF performance of devices and integrated circuits as a whole. Wetchemical etching is a conventional but important approach to conducting recess etching due to its ease of use and its capability to tailor device performance. To precisely control the gate recess process, the implantation of an etch-stop layer into the p-HEMT device structure is highly desirable. AlAs is a traditional etch-stop material to GaAs because of its high etching selectivity (~ 400x) and near perfect lattice match. For a reliable and controllable etching process, a reasonable thick etch-stop is desired. However, due to its large bandgap (~2.2eV) and higher defect density (DX center, for example), thick AlAs layer may cause ohmic contact problem and other side-effects which would degrade the device performance. We report the study of MBE growth of AlGaAs/InGaAs pHEMT structure with double AIAs etch-stop layers. The thickness of the AIAs etch-stoppers

Tuesday Evening Poster Sessions, October 3, 2000

ranging from 1.0 to 2.5 nm. The structures were studied by Hall measurement, high-resolution x-ray diffraction, photoluminescence (PL) and photoreflectance (PR). The selective etching behavior was verified by etching profiles of time dependent sheet charge density from Hall measurements. The correlation between the etching selectivity and ohmic contact resistivity, as well as the device performance of the p-HEMT structure was compared for different structures to get the optimum AlAs thickness.

EL-TuP7 Early Growth Studies of Barium Magnesium Fluoride onto (111)oriented Silicon Substrates, A. Martinez, W. Gomez, M. Rodriguez, University of Puerto Rico

We have grown barium magnesium fluoride films (BMF) onto (111)oriented silicon substrates using molecular beam epitaxy. The early stages of growth were studied through the performance of X-ray photoelectron spectroscopy measurements on interrupted growth runs without exposing films to atmosphere. It was observed that exposure of the Si substrate to the BMF vapor at a substrate temperature of 950C for periods of 10 seconds, removed the native oxide layer from the substrate. Subsequent growth onto substrates pretreated in this way resulted in highly textured (020)-oriented BMF films, as evidenced by x-ray diffraction studies. Films grown without the pretreatment did not display this high degree of texture.

EL-TuP8 Fabrication of Smooth Diamond Films on SiO2 by the Addition of Nitrogen to the Gas Feed in Hot-filament CVD, V. Baranauskas, A.C. Peterlevitz, Z. Jingguo, S.F. Durrant, Universidade Estadual de Campinas, Brazil

Diamond films of low roughness have been deposited onto thermally oxidized Si substrates by a process of anisotropic crystalline growth induced by nitrogen in a Hot-Filament Chemical Vapor Deposition (HFCVD) reactor. Ethanol (C2H5OH), diluted in hydrogen and nitrogen, was used as the source of carbon. At high concentrations, nitrogen tends to suppress diamond growth in the < 100 > direction, which allows the growth of square mesoscopic crystals of great area in the directions parallel to the surface of the substrate. These mesoscopic structures of low thickness stack upon each other, forming a thick diamond coating of uniform thickness. Analysis of the coatings made by micro-Raman spectroscopy and atomic force microscopy (AFM) revealed that it is possible to obtain diamond coatings of high quality of roughness comparable that of the SiO2 at the diamond/SiO2 interface, and the roughness at the growth surface corresponds to the thickness of the steps of the mesoscopic structures. The microscopic mechanisms that involve the possible passivation of the diamond surface by nitrogen are also discussed.

EL-TuP9 Nanocrystalline Diamond and Nano-carbon Structures Produced using a High Argon Concentration in Hot-filament CVD, V. Baranauskas, A.C. Peterlevitz, H.J. Ceragioli, S.F. Durrant, Universidade Estadual de Campinas, Brazil

Nanocrystalline diamond and nano-carbon structures in the form of wires have been grown by the introduction of argon at high concentrations (60 % to ~ 99.5 % vol. Ar) into the feed mixture (ethanol and hydrogen) of a hot-filament CVD reactor. Besides the chemical inertness of argon, its presence in the gas phase changes the kinetics of the carbon deposition process. The addition of argon induces an increase in the density of vacancy defects in the diamond structure, increases the flaws between the grains, the porosity of the films, and forms new carbon structures. The range of concentration of argon used in this work is very interesting since it covers the phase transition between porous diamond (~60 % vol. Ar) and carbon nanowires (~ 99.5 % vol. Ar). A critical discussion of the growth kinetics and morphological data obtained by scanning electron microscopy (SEM), micro-photoluminescence and micro-Raman spectroscopy are discussed.

EL-TuP10 Bonding Chemistry of Alternative Gate Dielectrics: Is there Really an Alternative Gate Dielectric that can Meet SIA Roadmap Expectations for Performance, Reliability and Process Integration?, *G. Lucovsky*, North Carolina State University

This paper presents a new classification scheme for non-crystalline metal oxides that have been considered as replacements for SiO@sub2@ in Si devices with channel lengths < 100 nm.. The scheme is based on relative bond ionicity, and the scaling parameter is the difference in the Pauling electronegativity, @Delta@X, between the oxygen, X(O), and metal (semiconductor), X(M), atoms. This approach distinguishes between three groups of non-crystalline elemental oxides with different bonding microstructures: i) @Delta@X < 1.6 - covalent random networks such as SiO@sub2@, B@sub2@O@sub3@, and P@sub2@O@sub5@, ii) 1.6<

@Delta@X < 2.0 - random amphoteric networks with interstitial ions such as Al@sub2@O@sub3@ and Ta@sub2@O@sub5@, and iii) @Delta@X > 2 - random close packed ionic structures such as Zr(Hf)O@sub2@, and Y(La)@sub2@O@sub3@. This approach has been extended to binary oxides and alloys. Systematic trends in atomic bonding arrangements and thermal stability with increasing @Delta@X are addressed for i) elemental oxides such as Al@sub2@O@sub3@, Ta@sub2@O@sub5@ and ZrO@sub2@, and ii) binary silicate alloys, such as (ZrO@sub2@)@subx@(SiO@sub2@)@sub(1-x)@ that span the entire range of @Delta@X. As @Delta@X increases, the atomic coordination of the metal atom increases, and thermal stability with respect to crystallization decreases. Three factors limit application of alternative oxides/silicates with @Delta@ X> 1.6 as gate dielectrics in Si devices. These are i) reactions with Si substrates, and/or intentionally-grown thin SiO@sub2@ interfacial layers that occur during film deposition and/or annealing, ii) thermal stability against chemical phase separation and/or crystallization which limits post-deposition processing temperatures, and iii) an inherent ion polarization contribution to the frequency dependent conductance that can degrade high frequency electrical performance.

EL-TuP11 Electrical Properties of (Ba,Sr)TiO@sub 3@ Capacitors by Inductively Coupled Plasma Etching, S.-K. Choi, N.-H. Kim, E.-G. Chang, Chungang University, Korea; T.-H. Kim, YIT, Korea; C.-I. Kim, Chungang University, Korea

Recently, (Ba,Sr)TiO@sub 3@ high dielectric thin films have received much attention as a new dielectric material for high density dynamic random access memories (DRAMs) because of their high relative dielectric constant and small variation in dielectric properties with frequency. It is well known that BST films are difficult to be etched, but good etch rate with high selectivity to etch mask was obtained by result of our former study.@footnote 1@ However, It was scarcely verified the possibility of etched thin films under these conditions for the appliance of practical devices. In this study, high density plasmas etching damage to the electrical properties of Pt/(Ba,Sr)TiO@sub 3@/Pt high dielectric capacitors was evaluated under Ar bombardment and Ar/Cl@sub 2@/BCl@sub 3@ etch plasmas. And the etch parameters were changed as gas mixing ratio, coil rf power, dc bias voltage and chamber pressure. Capacitance and leakage current of BST capacitors, before and after etching, are compared to examine the etching damage. The capacitance and dielectric dissipation factors were measured by using an HP 4192 impedance/gain-phase analyzer at 10 kHz, and the leakage current density was determined by using an HP 4145B semiconductor parameter analyzer. The change of capacitance and leakage current represented the physical effect of ion bombardment. The crystal structure of the etched samples was investigated by x-ray diffraction (XRD) to observe the variation of phases. The improved etching condition with the consideration of capacitance and leakage current of BST capacitor could be obtained by analyzing correlation between electrical properties and various etching parameters. @FootnoteText@ @footnote 1@ S.-B. Kim, Y.-H. Lee, T.-H. Kim, G.-Y. Yeom, and C.-I. Kim, J. Vac. Sci. Technol. A 18, 2000. To be published.

EL-TuP12 (1-x)SrTiO@sub 3@-xPbTiO@sub 3@ Thin Films Grown by RF Sputtering on Pt/TiN@sub X@ AND RuO/TiN@sub X@ Electrodes, *E.M. Guerra*, CICESE, Mexico; *A.F. Cruz*, IMRE, Mexico; *J.S. Beltrones*, UNAM, Mexico

(1-x)SrTiO@sub3@(ST)-xPbTiO@sub 3@(PT)polycrystalline thin films were deposited at different temperatures and pressures by argon ion rf sputtering on Pt/TiN@sub x@/SiO@sub 2@/Si and RuO/TiN@sub x@/SiO@sub 2@/Si substrates in presence of different concentration of Oxygen. The polycrystalline (ST-PT) perovskite phase formation is confirmed by x-ray diffraction (XRD) analysis and the grain growth dynamics is studied by scanning electron microscopy (SEM). The nature of the ferroelectric layer-electrode interface is analyzed by transmission electron microscopy (TEM) as well as the effect of its characteristics in the performance of the multilayer system. The dielectric properties of the ST-PT thin films were characterized through P-E hysteresis measurements. The microstructural results obtained for the (1-x)SrTiO@sub 3@-xPbTiO@sub 3@ films on Pt/TiN@sub x@/SiO@sub 2@/Si and RuO/TiN@sub x@/SiO@sub 2@/Si and RuO/TiN@sub x@/SiO@sub 2@/Si substrates were correlated to the ferroelectric properties.

EL-TuP13 Etching Mechanism of Y@sub 2@O@sub 3@ Thin Flims in Cl@sub 2@/Ar Plasma, Y.C. Kim, B.J. Min, Chungang University, Korea; Y.T. Kim, KIST, Korea; C.-I. Kim, Chungang University, Korea

Many researchers have proposed to insert such buffer layers as Y@sub 2@O@sub 3@ and CeO@sub 2@ for ferroelectric gate structures. In

Tuesday Evening Poster Sessions, October 3, 2000

particular, Y@sub 2@O@sub 3@/Si shows excellent interface properties and ferroelectrics deposited on Y@sub 2@O@sub 3@ film show excellent fatigue characteristics. The dielectric constant of Y@sub 2@O@sub 3@ film ranges from 14 to 17. Hence, Y@sub 2@O@sub 3@ films are expected to be used a buffer layer in the ferroelectric gate structure. In this study, etching mechanism of Y@sub 2@O@sub 3@ thin film was systematically investigated by using inductively coupled Cl@sub 2@/Ar plasma. Etching characteristics of the Y@sub 2@O@sub 3@ thin film were investigated by using plasma diagnostic tools in conjunction with the surface analysis after etching. The etch rate of Y@sub 2@O@sub 3@ film, and selectivity of Y@sub 2@O@sub 3@ film to PR and SiO@sub 2@ were examined as functions of Cl@sub 2@/Ar gas mixing ratio, coil rf-power, dc bias voltage, chamber pressure, and substrate temperature. The etched surface of Y@sub 2@O@sub 3@ film was examined with x-ray photoelectron spectroscopy (XPS) and secondary ion mass spectrometry (SIMS). The etch profile of Y@sub 2@O@sub 3@ film was examined with scanning electron microscopy (SEM). The concentrations of the etching species in the plasma were determined by using optical emission spectroscopy (OES). Plasma potential and floating potential, electron density and ion current density in the plasma were determined by using Langmuir probe. Y@sub 2@O@sub 3@ film was more effectively etched by Ar ion bombardment than by chemical reaction with Cl radical, but the etch rate of Y@sub 2@O@sub 3@ film was enhanced by chemical reaction with Cl radical. In this study, for the first time, we introduced the use of Cl@sub 2@/Ar plasma system in Y@sub 2@O@sub 3@ etching.

EL-TuP14 Etch Characteristics of CeO@sub 2@ Thin Films as a Buffer Layer for the Applications of MFIS-FeRAM, C.-S. Oh, Chungang University, Korea; *K.-H. Kwon*, Hanseo University, Korea; *T.-H. Kim*, YIT, Korea; *C.-I. Kim*, Chungang University, Korea

Cerium oxide (CeO@sub 2@) thin film has been proposed as a buffer layer between the ferroelectric film and the Si substrate in Metal-Ferroelectric-Insulator-Silicon (MFIS) structures for ferroelectric random access memory (FeRAM). CeO@sub 2@ thin film has properties of high thermal stability, high dielectric constant and good lattice match with Si. Since the etching of CeO@sub 2@ thin film has not been reported, we studied the etch characteristics of CeO@sub 2@ thin films by using high density plasma etching system. In this study, CeO@sub 2@ thin films were etched with a CF@sub 4@/Ar gas combination in an inductively coupled plasma (ICP). Mask made use of photoresist (PR). The experiment was done by controlling the etching parameters such as gas mixing ratio, radio frequency power, direct current bias, and chamber pressure. The surface reaction of the etched CeO@sub 2@ thin films was investigated with x-ray photoelectron spectroscopy (XPS) using narrow scan spectra. Ar ion bombardment is more dominant than chemical reaction between Ce and F. The results of XPS analysis were verified by results of secondary ion mass spectrometer (SIMS) analysis and results were the same. In addition, Optical emission spectroscopy (OES) was investigated to analyze density of F radical and Ar ion in plasma. Ion current density was measured by using single Langmuir probe. The etch products were also determined using a quadrupole mass spectrometer (QMS). The profile of etched CeO@sub 2@ thin film investigated with scanning electron microscopy (SEM).

EL-TuP15 The Interface Formation of Ta and Low-k Plasma-polymerized Para-xylene (PPpX) and Cyclohexane (PPCHex) and the Diffusion Properties, K.J. Kim, K.S. Kim, Y.C. Jang, Sungkyunkwan University, South Korea; G.Y. Yeom, N.-E. Lee, Sungkyunkwan University, South Korea; Korea; Y.C. Quan, J. Choi, C.Y. Park, Sungkyunkwan University, South Korea; D.-Y. Jung, Sungkyunkwan University, South Korea

In order to decrease the RC delay of integrated circuit, there have been extensive research activities on Cu interconnect technology utilizing low dielectric constant (low-k) interlayer dielectric materials and Cu to replace the conventional AI metallization scheme. One of the candidates for low-k dielectrics is the organic thin films prepared by various methods. Particularly, low-k plasma-polymerized organic films containing no F which causes various corrosion problems are very promising. However, they do not provide a good interfacial adhesion to metals due to the absence of bonding states between metals and plasma-polymerized low-k organic films. In this study, we investigated the interface formation and diffusion properties between Ta and low-k plasma-polymerized para-xylene (PPpX) and cyclohexane (PPCHex) thin films as a function of O@sub 2@ or N@sub 2@ plasma-treatment conditions using XPS and RBS. Low-k plasmapolymerized thin films were prepared on silicon substrates by PECVD using the para-xylene and cyclohexane precursors at the substrate temperature of 45°C. PPpX and PPCHex were shown to have the dielectric constant as low as 2.70 and thermal stability up to 450°C. Plasma-treatments were

performed by MEICP at the inductive power of 400W by keeping the O@sub 2@ and N@sub 2@ flow at 10sccm, respectively. Ta with the film thickness of 40Å was deposited using an electron-beam evaporator at room temperature. These samples were annealed at 450 ~ 500°C in vacuum in order to investigate the interface formation and diffusion of Ta into low-k films. We found that the Ta-C, due to newly created additional functional group, was formed between Ta layer and plasma-treated low-k films, judged from XPS measurements. The diffusion of Ta into the PPpX and PPHex was negligible in the detection limit of RBS.

EL-TuP16 Structure Effects of Pendant Groups on Dielectric Constant and Thermal Properties of Polyimides, *L.-Y. Wang*, National Taiwan University, Taiwan; *P. Chang*, *C.-L. Cheng*, Chung-Yuan University, Taiwan

Polyimides exhibit high thermal and mechanical properties, are easily processable as thin films from soluble precursors, and have desirable dielectric properties. In this study, we investigate the structure-property on a series of polyimides which contain alkyl side groups. Two series of high molecular weight polyimides have been synthesized by the reaction of benzophenonetetracarboxylic dianhydride (BTDA) or hexafluoroisopropylidene bis(phthalic anhydride) (6FDA) with 4,4'methylenedianiline (MDA), 4,4'-methylene-bis-(2,6-dimethylaniline) (MBDMA), 4,4'-methylene-bis-(2,6-diethylaniline) (MBDEA) or 4,4'methylene-bis-(2,6-diisopropylaniline) (MBDIA). The introduction of fluorine into polyimides may vary free volume and polarizability and effect dielectric constant and thermal properties. The introduction of different side groups may change free volume and effect dielectric property. In this research, a detailed structure effect on the dielectric constant and thermal properties of polyimides containing alkyl side groups will be illustrated.

Dielectrics

Room 312 - Session DI+EL+MS-WeM

Low K Dielectrics

Moderator: J.A. Kelber, University of North Texas

8:20am DI+EL+MS-WeM1 Ultra Low k Mesoporous Silica Dielectrics for Semiconductor Interconnects, S. Baskaran, J. Liu, X. Li, C. Coyle, J. Birnbaum, G.C. Dunham, G.E. Fryxell, Pacific Northwest National Laboratory; C. Jin, International SEMATECH INVITED The semiconductor industry is currently targeting new intermetal dielectric (IMD) films with dielectric constants (k) less than 2.5 for interconnect applications in the 100 nm technology node, and films with k less than 2.0 for the 70 nm technology node. To meet extreme low k needs for advanced on-chip interconnects, films with incorporated porosity will most certainly be required. Porous dielectric films with k values less than 2.2 ("ultra low k") are not easily synthesized using conventional vacuum based technology such as chemical vapor deposition. A simple approach to nanoporous dielectric films involves spin-on deposition of formulations consisting of silicate, polymeric, or hybrid organosilicate precursors with thermally degradable pore-formers. Ultra low k mesoporous silica films have been synthesized with molecularly templated porosity using this approach. Molecularly organized nanostructured aggregates between 2 and 10 nm in size can function as templates for pore formation in spin coated sol-gel silicate films. The use of a structurally organized template during synthesis results in a uni-modal pore size distribution in the final film. In this paper, we present information on precursor chemistry for designing mesoscale porosity, pore architecture and surface chemistry, and the critical dielectric and mechanical properties for mesoporous silica films. Using formulations developed at PNNL, mesoporous films have also been prepared at SEMATECH on production-size wafers, and evaluated. Copper single-damascene one-level test structures were built using mesoporous silica as the intermetal dielectric. No major structural failures were observed after chemical mechanical planarization on both blanket films and patterned wafers, indicating relatively good mechanical integrity for a With controlled film synthesis and highly porous structure. dehydroxylation conditions, mesoporous silica films with k@super 2@ 2.0 and elastic modulus of 4.0 GPa have been synthesized at PNNL. The results of the one-level metal screening tests at SEMATECH combined with properties obtained at PNNL indicate that mesoporous molecularlytemplated silicate films hold promise as ultra low k intermetal dielectrics.

9:00am DI+EL+MS-WeM3 Deposition of Thermal Stable Amorphous Carbon Nitride Thin Films with Low Dielectric Constant by ECR-CVD, X.W. Liu, National Tsing Hua University, Taiwan, ROC, Taiwan, ROC; J.H. Lin, National Tsing Hua University, Taiwan, ROC; H.C. Shih, National Tsing Hua University, Taiwan, ROC

Amorphous carbon nitride thin films with low dielectric constants and high thermal stability were synthesized on silicon by using an electron cyclotron resonance chemical vapor deposition (ECR-CVD) system in which a rf bias was applied to the silicon substrate and a mixture of C@sub 2@H@sub 2@, N@sub 2@ and Ar was used as precursors. The dielectric constants of our amorphous carbon nitride thin films were found as low as 2.4 at 1 MHz. The thermal stability of the films has been improved by the incorporation of nitrogen to the carbon film. The basic structure, composition and electronic properties of these films were analyzed by Fourier transformation infrared (FTIR) spectroscopy, Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM), and field emission scanning electron microscopy (FE-SEM) and dielectric constant measurements.

9:20am DI+EL+MS-WeM4 Impact of Hydrogen Addition on the Deposition Rate of SiOF Films Prepared by High Density Plasma CVD, Y.W. Teh, Nanyang Technological University, Singapore; T.C. Ang, Chartered Semiconductor Manufacturing, Singapore; K.S. Wong, Nanyang Technological University, Singapore; K.H. See, S.Y. Loong, Y.C. Wong, Chartered Semiconductor Manufacturing, Singapore

Fluorinated Silicon Dioxide film (SiOF) has been considered as the more successful first generation interlevel low-k dielectric material. However, the impact of hydrogen addition on SiOF film properties are not extensively studied. In this paper, we present a spectroscopic study of the chemical bonding in SiOF film grown with silane gas added to the standard precursors using the techniques of ellipsometry and infrared (IR) absorption spectroscopy. These SiOF films have been prepared by high density plasma (HDP) chemical vapor deposition at substrate temperature at about 420°C. Addition of hydrogen through silane gas feed is found to control deposition rate and the fluorine doping concentration of the SiOF films. The addition of SiH4 does not lead to the incorporation of hydrogen in detectable quantities in the SiOF films. This phenomenon may be attributed to the strong mutual attraction between hydrogen and fluorine radicals in the HDP. The decrease of refraction index at 632.8nm and the frequency decrease of the dominant IR active bond-stretching vibration at ~1085cm@super -@@super 1@ were found to be approximately linear with increase in fluorine concentrations. The silane added to the process gas mixture has been found to play an active role in the SiOF film formation process both in the surface reactions and the chemical bonding properties. Our results show that with an optimized silane flow rate, the film stability of the SiOF towards moisture attack is significantly improved. In addition, a high deposition rate can be achieved together with comparable fluorine incorporation in the film as compared to the standard non-silane precursors.

9:40am DI+EL+MS-WeM5 Solid-state Nuclear Magnetic Resonance of Low Dielectric Constant Si:O:C:H Films, P.-Y. Mabboux, K.K. Gleason, Massachusetts Institute of Technology

Adding organic content to SiO@sub 2@ is an evolutionary pathway to low dielectric films with k @<=@ 3.0. Alternate names for these materials include carbon-doped oxides, organosilicate glasses (OSG), and Si:O:C:H films. Both spin-coating and chemical vapor deposition (CVD) processes have been developed for this class of low-k films. Fourier transform infrared spectroscopy (FTIR) and x-ray photoelectron spectroscopy (XPS) have only a limited ability to distinguish variations in Si:O:C:H film chemistry. In this work, solid-state nuclear magnetic resonance (NMR) is shown to have sufficient sensitivity to determine the network structure of low dielectric constant Si:O:C:H films. Characterization of Si:O:C:H films by @super 1@H, @super 13@C, and @super 29@Si magic-angle spinning NMR will be demonstrated. Because of its wide range of chemical shifts, @super 29@Si NMR is particularly useful to elucidate new details regarding the composition and structure of these low dielectric constant films. Up to ten different environments can be resolved in some of the films. Many of the observed chemical bonding configurations have been previously observed in bulk organosilicate glasses. The NMR results can be expressed in terms of a connectivity number, which is simply the average number of bonds between network forming atoms. The connectivity number may provide a means to correlate with the mechanical properties. Fundamental understanding of structure-property-processing relationships will facilitate the engineering of the molecular architecture required for successful integration of Si:O:C:H dielectric films.

10:00am DI+EL+MS-WeM6 A New Simple and Accurate Method to Measure Intra-Metal Capacitance of Low-K Fluorinated Silicon Dioxide, K.S. Wong, Y.W. Teh, Nanyang Technological University, Singapore; T.C. Ang, S.Y. Loong, W.B. Loh, Y.C. Wong, Chartered Semiconductor Manufacturing, Singapore

An accurate and simple technique for intra-metal capacitance measurement is presented. This on-chip technique is based on a test structure design that utilizes only interdigitated capacitors sandwiched between metal plates. Compared to other techniques which utilize transistors in addition to the unknown interconnect capacitance to be characterized, this new technique requires only capacitors and thus much simpler processing and shorter cycle times but with the same level of accuracy. With this test structure design, no reference capacitor is needed. Capacitance voltage (C-V) method is commonly used for intra-metal capacitance measurement. However, the measurement accuracy is often compromised by probe-induced stray capacitance. In this paper, a new measurement technique that can eliminate this stray capacitance is reported. This new technique uses multiple probe configurations to obtain 3 capacitance values and these values can be used to eliminate the probeinduced stray capacitance and obtain the actual intra-metal capacitance. Results show much better accuracy than the conventional C-V measurement. Comparisons between the new technique, the conventional C-V measurement and the Charge-Base Capacitance Measurement (CBCM) techniques are made. Our results based on the new technique show great improvement in the measurement accuracy over the conventional technique. In addition, our results are consistent with the results obtained from the CBCM technique which requires the use of transistors and thus more complex processing and longer cycle times. In this paper, the different measurement techniques were evaluated on high-density plasma chemical vapor deposition (HDP-CVD) fluorinated silicon dioxide (SiOF) inter-level dielectric (IMD) films in 0.18um technology.

10:20am DI+EL+MS-WeM7 DC and RF Characteristics of Advanced MIM Capacitors for MMIC's Using Thin and Low Temperature PECVD Si@sub 3@N@sub 4@ Dielectric Layers, C.R. LIM, J.H. LEE, S.W. Paek, K.W. Chung, LG-ELITE, Republic of Korea

In this work, we show the excellent DC and RF characteristics of MIM (metal-insulator-metal) of PECVD Si@sub 3@N@sub 4@ thin film deposited at 85°C. The breakdown field strength of MIM capacitors with 490 Å Si@sub 3@N@sub 4@ was larger than 4.1 MV/cm which indicates the excellent quality of the deposited Si@sub 3@N@sub 4@ film. The main capacitance of unit area extracted by RF (radio frequency) measurements was 1240 pF/mm@super2@. So, its high capacitance enables us to reduce the size of MIM to a quarter size compared with the conventional MIM having 2000 Å Si@sub 3@N@sub 4@. In spite of its thin thickness of dielectrics, RF characteristics showed good performance. Above all, it was fabricated at low temperature, so we were able to develop the process of MIM fabrication using dielectric lift-off. At this point, the thickness adapted in dielectric lift-off process was about 1000 Å for adjusting capacitance to a designed capacitance.

10:40am DI+EL+MS-WeM8 Rapid Prototyping by Local Deposition of Siliconoxide and Tungsten Nanostructures for Interconnect Rewiring, *H.D. Wanzenboeck, S. Harasek, H. Langfischer, A. Lugstein, E. Bertagnolli,* Vienna University of Technology, Austria

The local deposition of dielectric material and metal wires as typically used for rewiring of interconnect layers has been demonstrated to be a promising approach for rapid prototyping of integrated circuits. With an ion beam induced surface reaction dielectric structures were fabricated with a selected geometric configuration in dimensions ranging from several hundred µm down to the deep sub-µm scale displaying the potential application in interconnect modification. A focused Ga ion beam at 50 kV acceleration voltage was applied to induce the surface decomposition of gaseous precursors. A dynamic adsorption state was achieved characterized by the equilibrium between influx through a nozzle system and the outlet through the vacuum pump. Siliconoxide was obtained by using siliconorganic compounds and oxygen as precursor adsorbed on the surface at a total pressure typically between 10E-5 to 10E-6 Torr. Conductive W-structures were obtained using W(CO)6. The suitability for practical applications in microelectronics has been demonstrated by measuring the electrical properties of deposited dielectrics using test vehicles with a metal-insulator-metal (MIM) capacitor setup. The thickness of the dielectric laver was varied between 70 nm and 1.4 Âum. The resistivity and capacitance of FIB deposited dielectrics was found to vary with deposition parameters such as exposure time and scanning rate of the ion beam. A chemical characterization of the fabricated dielectric layers has been performed. The electrical properties of locally deposited dielectrics were correlated with the material composition of the deposited material. The suggested optimized deposition process can provide improved dielectrics suitable as interline and interlayer insulator for a complex microelectronic interconnect architecture.

Magnetic Interfaces and Nanostructures Room 206 - Session MI+EL-WeM

Magnetic Semiconductors and Hybrid Structures I

Moderator: B. Jonker, Naval Research Laboratory

8:20am MI+EL-WeM1 Characterizations of MBE Grown Single Crystal Ferromagnetic Ni@sub 2@MnGa Thin Films on (001) Ga@sub 1x@In@sub x@As, J.W. Dong¹, J.Q. Xie, L.C. Chen, M.T. Figus, S. McKernan, C.J. Palmstrom, University of Minnesota

Minimization of spin flip scattering at the interface of ferromagnetic metal/semiconductor is expected with the use of high quality epitaxially grown ferromagnetic metal/semiconductor heterostructures with minimal interfacial reactions. The Heusler alloy Ni@sub 2@MnGa is ferromagnetic at room temperature and has the cubic L2@sub 1@ Heusler structure with lattice parameter 3% larger than that of GaAs. We have demonstrated MBE growth of 900 Å-thick single crystal Ni@sub 2@MnGa on (001) GaAs with a 6 monolayer-thick Sc@sub 0.3@Er@sub 0.7@As interlayer, which acts as a template layer and a diffusion barrier. Reflection high energy electron diffraction, X-ray diffraction, and transmission electron microscopy (TEM) studies confirm the single crystal structure of the Ni@sub 2@MnGa films and indicate that the growth is pseudomorphic on GaAs substrates. These results suggest an epitaxially stabilized tetragonal phase of Ni@sub

2@MnGa with a = b = 5.65 Å, c = 6.12 Å, which has not been found in the bulk. High resolution cross section TEM image shows that the interface between Ni@sub 2@MnGa films and the Sc@sub 0.3@Er@sub 0.7@As interlayer is atomically abrupt. The Rutherford backscattering channeling minimum yield of 6.5% further confirms the high quality of the Ni2MnGa films. At room temperature, magnetic measurements using a vibrating sample magnetometer show that the films are ferromagnetic with a coercivity of ~50 Oe, a saturation magnetization of ~250 emu/cm@super 3@, and a weak in-plane magnetic anisotropy. Using a superconducting quantum interference device magnetometer, the Curie temperature of the films is found to be ~340 K. Our results indicate that Ni@sub 2@MnGa/GaAs can form high quality ferromagnetic metal/semiconductor heterostructures that might be used for spin injection measurements. In this talk, the effect of interlayer and strain on the structural and magnetic properties of Ni@sub 2@MnGa on Ga@sub 1-x@In@sub x@As substrates will be discussed.

8:40am MI+EL-WeM2 Molecular Beam Epitaxial Growth of Ferromagnetic Ni@sub 2@MnGe on GaAs(001), J. Lu, J.W. Dong, J.Q. Xie, D. Carr, University of Minnesota; V. Godlevsky, Rutgers University; C.J. Palmstrom, University of Minnesota

A number of Heusler (L2@sub 1@) structures such as Ni@sub 2@MnX (X = Ga, In, Sn, Sb) are ferromagnetic shape memory alloys. The ferromagnetic Heusler alloys show promise as single crystal ferromagnetic spin polarized injecting contacts to semiconductors. In this work, epitaxial thin films of the Heusler alloy Ni@sub 2@MnGe have been for the first time grown on GaAs(001) substrate by molecular beam epitaxy (MBE). A two step growth procedure was used which included alternate layer epitaxy at 200°C of a thin Ni@sub 2@MnGe template layer followed by codeposition at 250°C. A (2x2) surface reconstruction was observed by in-situ reflection high energy electron diffraction. X-ray diffraction studies show that the Ni@sub 2@MnGe film is epitaxially grown on GaAs(001) with the crystallographic relationship: (001)@sub Ni2MnGe@//(001)@sub GaAs@, (110)@sub Ni2MnGe@//(110)@sub GaAs@ . X-ray diffraction was used to determine both the out of plane and in plane lattice parameters. These confirmed that the film had a tetragonal structure, with a = 5.65 ± 0.02 Å c = 5.897 Å, and c axis perpendicular to film surface, suggesting pseudomorphic growth on the GaAs surface. The magnetic properties were measured using superconducting quantum interference device magnetometry (SQUID). The coercivity of the film is ~50 Oe, and the saturation magnetization Ms is ~ 200 emu/cm3. The Curie temperature was 330 ± 10 K. In this talk, the magnetic and structural properties of Ni@sub 2@MnGe/GaAs heterostructures as a result of growth procedures and composition will be discussed. Results from Rutherford backscattering and transmission electron microscopy studies will be correlated with the magnetic properties

9:00am MI+EL-WeM3 Demonstration of Electrical Spin Injection: The Spin-LED@footnote 1@, Y.D. Park, B.R. Bennett, B.T. Jonker, Naval Research Laboratory; H.-D. Cheong, G. Kioseoglou, A. Petrou, SUNY, Buffalo Electrical spin injection into a semiconductor is a prerequisite for realizing the potential of semiconductor-based spintronic devices. This has been an elusive goal, however, and only modest effects (@<=@ 1%) have been obtained. We report here highly efficient electrical spin injection from a magnetic contact into a GaAs quantum well-based light emitting diode (LED) heterostructure (a spin-LED@footnote 2,3@) in which the spin injection efficiency exceeds 50%. Radiative recombination of spin polarized carriers in quantum wells results in the emission of circularly polarized light. The degree of optical polarization is proportional to the carrier spin polarization, enabling a direct, quantitative measure of the spin injection efficiency. The samples consist of ZnSe/ZnMnSe/AlGaAs/GaAs/AlGaAs heterostructures grown by MBE on p-GaAs(001) substrates, where the semimagnetic semiconductor ZnMnSe serves as a source of spin-polarized electrons which are injected via an applied bias voltage into the GaAs quantum well. Standard optical lithography and chemical etch procedures were used to define surface emitting LED mesa structures. The measured circular polarization of the electroluminescence (EL) exceeds 50%, and demonstrates that highly efficient spin transport occurs across the ZnMnSe/AlGaAs interface despite the large 0.5% lattice mismatch. Data are reported as a function of injection current, magnetic field, and temperature. The EL lineshape consists of multiple components whose relative polarization provide insight into spin relaxation mechanisms. We compare results from ex situ and in situ contacts, and with those obtained for carefully lattice matched systems.@footnote 4@. @FootnoteText@ @footnote 1@ This work was supported by the Office of Naval Research. @footnote 2@ US patent #5,874,749 (filed 6/93; awarded 2/99)

@footnote 3@ Jonker, et al., submitted for publication. @footnote 4@ Fiederling, et al., Nature 402, 787 (16 December 1999).

9:20am MI+EL-WeM4 Ferromagnetism and Spin Related Phenomena in Semiconductor Heterostructures, H. Ohno, Tohoku University, Japan INVITED

Alloys between non-magnetic III-V semiconductors and Mn have been grown by molecular beam epitaxy and shown to exhibit ferromagnetism at reduced temperatures. These alloys, (Ga,Mn)As, (In,Mn)As, and (Ga,Mn)Sb are guasi-lattice matched to their host semiconductors and thus offer new and unique opportunities to combine ferromagnetism and high quality III-V heterostructures being widely used in frontiers of semiconductor physics and also in commercially available devices. This talk covers the following topics: (1) Preparation and properties of ferromagnetic semiconductors, particularly (Ga,Mn)As, where transition temperature can be as high as 110 K for 5% Mn concentration.@footnote 1@ (2) The origin of carrier-induced ferromagnetism based on a mean field theory using kp approximation.@footnote 2@ (3) Ferromagnet/non-magnet tri-layer semiconductor structures exhibiting inter-layer magnetic coupling and spin-dependent scattering.@footnote 3@ (4) Resonant tunneling structures with ferromagnetic emitters.@footnote 4@ (5) Spin-injection experiments using ferromagnetic semiconductor heterostructures.@footnote 5@ (6) Spin relaxation in nonmagnetic (110) GaAs quantum wells, where prolonged spin relaxation times are observed,@footnote 6@ which can be over 10 ns from room temperature down to 5 K when modulation doped. @FootnoteText@ @footnote 1@ H. Ohno, Science, 281, 951 (1998), J. Mag. Mag. Materials, 200, 110 (1999). @footnote 2@ T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, Science, 287, 1019 (2000). @footnote 3@ N. Akiba, D. Chiba, K. Nakata, F. Matsukura, Y. Ohno, and H. Ohno, J. Appl. Phys., 87, 6436 (2000). @footnote 4@ H. Ohno, N. Akiba, F. Matsukura, A. Shen, K. Ohtani, and Y. Ohno, App. Phys. Lett., 73, 363 (1998). @footnote 5@ Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, Nature, 402, 790 (1999). @footnote 6@ Y. Ohno, R. Terauchi, T. Adachi, F. Matsukura, and H. Ohno, Phys. Rev. Lett., 83, 4196 (1999).

10:00am MI+EL-WeM6 Properties of Mn@sub x@Ge@sub 1-x@, Cr@sub y@Ge@sub 1-y@ and Mn@sub x@Cr@sub y@Ge@sub 1-x-y@ Semiconductor Films Grown by Molecular Beam Epitaxy@footnote 1@, J.E. Mattson, Naval Research Laboratory, US; Y.D. Park, T.F. Ambrose, A.T. Hanbicki, A. Wilson, G. Spanos, B.T. Jonker, Naval Research Laboratory

Mn doped GaAs exhibits ferromagnetic ordering along with semiconducting behavior.@footnote 2,3@ Recent theory@footnote 4@ suggests that low concentrations of Mn (10@super 20@ cm@super -3@). We describe here the structural, magneto-transport, and magnetic properties of Ge@sub 1-x@Mn@sub x@, Ge@sub 1-y@Cr@sub y@ and Ge@sub 1-y-x@Cr@sub y@Mn@sub x@ thin films (with x < 0.15, and y < 0.15) in which Mn and Cr act as acceptors. Samples were grown by MBE on GaAs(001) and Si(001) substrates at substrate temperatures ranging from 175 to 350°C and growth rates of 4-5 Å/min. For all growth conditions studied, the GeMn films show a largely diffuse RHEED pattern and lack of structural order as determined by XRD. The temperature dependence of the resistivity shows non-metallic behavior with room temperature hole concentrations as high as 3x10@super 20@cm@super -3@. The magnetic properties determined from SQUID magnetometry are similar to those of Ge@sub 8@Mn@sub 11@ bulk alloys, suggesting the formation clusters of Ge@sub 8@Mn@sub 11@ rather than a homogeneous alloy. Plan-view TEM confirms the presence of clusters. The GeCr films exhibit single crystal growth and are p-type with p

10:20am MI+EL-WeM7 Characterizations of Fe Thin Films on GaAs (001) Grown at Cryogenic Temperatures by Molecular Beam Epitaxy, Y. Chye, P Petroff, University of California, Santa Barbara

One of our research objectives is to fabricate hybrid structures by integrating ferromagnetic materials into semiconductors. It has been demonstrated that molecular beam epitaxy (MBE) can be used to fabricate single crystalline Fe directly upon GaAs.@footnote 1@ However, the intermixing between Fe and GaAs at the interface forms a "magnetically dead layer"@footnote 1@ which will badly affect polarized transport and thus make efficient "spintronics" devices hard to realize. In an effort to circumvent this problem, we propose to grow Fe on GaAs at cryogenic temperatures (below -100 ° C). At these temperatures, the deposited Fe atoms and the GaAs surface atoms are less likely to react with each other through interdiffusion. To implement these ideas, we grow Fe thin films on GaAs (001) semi-insulating substrates at -150 ° C in an EPI-620 MBE with a liquid-nitrogen cooled sample stage. It is indicated by the streaky RHEED

pattern that single crystalline Fe is grown on GaAs. The surface morphology, interface properties, crystal structure, film orientation and magnetic behavior of the samples have been characterized by atomic force microscopy (AFM), transmission electron microscopy (TEM), x-ray diffraction, and superconductivity quantum interference device (SQUID), respectively. To examine the interdiffusion at the interface, we perform photoluminescence (PL) measurements for samples with very thin Fe films grown at different temperatures above GaAs quantum wells. Our results show that the PL peaks for the quantum wells do not significantly change for the cryogenic temperature grown samples, whereas the room temperature grown samples show a dramatically reduced luminescence efficiency and energy emission shift. These results suggest that the cryogenic temperature deposition strongly suppress the interdiffusion between the Fe and GaAs at the interface. @FootnoteText@ @footnote 1@ J. J. Krebs, B. T. Jonker, G. A. Prinz, J. Appl. Phys., 61 (1987) 2596.

10:40am MI+EL-WeM8 Growth and Magnetic Properties of Epitaxial Fe-N Films@footnote 1@, F. Liu, S.-C. Byeon, C. Alexander, G.J. Mankey, University of Alabama

Reported values of magnetic moments in epitaxial Fe@sub 16@N@sub 2@ films vary from 2.3 to 3.5 Bohr magnetons per atom.@footnote 2@ These discrepancies arise from the fact that the films are multiphase mixtures which decompose upon heating.@footnote 3@ To study this problem, 40 nm thick Fe-N films were produced using reactive sputtering in an ultra clean sputtering system with in situ RHEED. First, an S-terminated GaAs surface is prepared by wet chemical etching. After annealing at 450 C, a 3 nm thick Fe seed layer is deposited to promote epitaxial growth of a 20 nm thick Ag(100) buffer layer. The Fe-N film is then grown on this Ag(100) buffer. The sputtering power, Ar + N@sub 2@ pressure, and the substrate temperature were varied systematically to produce the optimal RHEED pattern. The films were capped with a 5 nm thick Ru layer for ex situ structural and magnetic analysis. XRD is used to identify the degree of Nsite ordering and the unit cell volume. XPS depth profiling is used to determine the chemical composition of the Fe-N film. The structural and chemical measurements are correlated with ferromagnetic resonance and vibrating sample magnetometry measurements of the saturation magnetic moment. These results are used to clarify the origin of the "giant magnetic moment" in the ordered Fe@sub 16@N@sub 2@ phase. @FootnoteText@ @footnote 1@Funded by ARO #DAAH 04-96-1-0316 and NSF #DMR-9809423. @footnote 2@G.W. Fernando et al., Phys. Rev. B 61, 375(2000). @footnote 3@ Migaku Takahasi and H. Shoji, J. Magn. Magn. Mater. 208, 145(2000)

Organic Films and Devices Room 313 - Session OF+EL+SS-WeM

Transport and Device Issues in Organic Thin Films Moderator: A. Kahn, Princeton University

8:20am OF+EL+SS-WeM1 The Transport and Injection of Positive Carriers in Conjugated Electroluminescent Polymers and their Devices, A.J. Campbell, University of Sheffield, UK, U.K.; D.D.C. Bradley, University of Sheffield, UK; H. Antoniadis, Infineon Technologies Corp. INVITED Organic light emitting diodes (OLEDs) based on electroluminescent conjugated polymers are an important emerging technology with a wide range of display and lighting applications. Polyfluorene and its copolymers are considered to be amongst the most promising materials for use in commercial OLEDs. Indium tin oxide (ITO) is also the hole injecting electrode of choice in any practical device. Here we report the results of time-of-flight measurements on the transport of positive carriers in polyfluorene and its copolymers. The field and temperature dependence of the charge carrier mobility is compared to theoretical models for charge transport in disordered organic materials. We also report the results of dark injection and current density-voltage measurements on the injection of holes from differently prepared ITO contacts. The absolute injection efficiency of the contacts is calculated by comparison to trap-free, spacecharge-limited current (TFSCLC). The injection efficiency is shown to vary with not only polymer ionisation potential but also with the nature of the ITO preparation (i.e. washed in solvents, exposed to an oxygen plasma, coated with a film of poly(ethylenedioxythiophene) / polystyrenesulphonic acid). The variation of the injection efficiency with temperature is also reported.

9:00am OF+EL+SS-WeM3 Grain Boundary Effects on Electrical Transport in Polycrystalline Organic Semiconductor Thin Films, *R.J. Chesterfield*, *A.B. Chwang*, *K. Puntambekar*, *C.D. Frisbie*, University of Minnesota

The role of microstructure in electrical transport in polycrystalline thin films of organic semiconducting oligomers (e.g., pentacene, sexithiophene) has not been extensively explored. This talk describes experiments in which transport through single grain boundaries (GBs) is probed using field effect transistor (FET) structures and Kelvin probe force microscopy (KPFM). In the FET studies, closely spaced gold source and drain electrodes are connected to pairs of pentacene or sexithiophene microcrystals grown on insulating substrates, such as SiO@sub 2@. The microcrystals, or grains, share a common boundary that dominates the transport through the FET. Conduction through the GB is measured as a function of gate field and temperature, and the results are compared with a recent model by Schon and Batlogg.@footnote 1@) In the KPFM studies, a metal-coated AFM tip is used to record potential distributions across an operating microcrystal FET. The resulting images reveal where the voltage is dropped across the device and thus point to the chief bottlenecks in the current transport. In general, both the microcrystal FET and Kelvin probe experiments show that microstructure, and in particular GBs, can potentially dominate transport in polycrystalline organic semiconductor films. @FootnoteText@ @footnote 1@J. H. Schon, B. Batlogg, Appl. Phys. Letters, 74(2), 1999, 260-262.

9:20am OF+EL+SS-WeM4 Quantum Confinement and Electron Transfer at Organic-Metal Interfaces, G. Dutton, H. Wang, X.-Y. Zhu, University of Minnesota

Electron transfer at organic-metal interfaces is important in moleculebased electronic and optoelectronic devices, such as light-emitting devices (LEDs), field-effect transistors (FETs), and molecular quantum wires (QW). We probe interfacial electronic structure and electron transfer dynamics using two-photon photoemission in model systems: thin films of hexafluorobenzene and naphthalene adsorbed on Cu(111). Electron transfer to the lowest unoccupied molecular orbitals, as well as to those mixed with image-type states, are observed. In both systems, these resonances display quantum well behavior: the electronic wavefunction is delocalized parallel to the surface but confined in the direction normal to the surface. The detailed structure and dynamics are established by dispersion measurements and by femto-second time-resolved two-photon photoemission. We believe the formation of these molecular quantum wells is a result of the strong interaction of molecular states with the metal substrate. A simple theoretical framework is developed to describe the formation of these molecular quantum wells.

9:40am OF+EL+SS-WeM5 Chemistry and Electronic Properties at Metals (Al, Mg and Au)-Organic Molecular Semiconductor (F@sub 16@CuPc) Interfaces, C. Shen, J. Schwartz, A. Kahn, Princeton University

The fabrication of efficient and stable metal-organic contacts is exceedingly important for the optimization of organic devices such as organic light emitting diodes (OLED) and thin film transistors. Al and Mg have low work functions and are typically used as electron injecting cathode materials. Au is a mostly inert metal in contact with organic materials. F@sub 16@CuPc is a candidate for n-channel thin film transistor material because of it relatively high electron mobility. Chemistry and physical processes (e.g. interdiffusion) that take place at metal/organic interfaces have a direct impact on the electronic properties of the contacts. It is generally believed that metals deposited on organics lead to more extensive interface chemistry and broader interfaces than organics deposited on metals. In some cases, these interfaces have actually been reported to lead to drastically different electrical behavior. The interfaces fabricated in ultrahigh vacuum, however, shows identical electrical behavior.@footnote 1@ We have investigated the interface chemistry, electronic structure and electrical transport in nominally symmetric metal/F@sub 16@CuPc/metal structures fabricated and tested in ultra-high vacuum. For these structures, we performed detailed ultra-violet and X-ray photoemission spectroscopy (UPS, XPS) photoemission spectroscopy measurements that suggest that the chemistry at metal-on-organic interfaces is very similar to, if not identical with, that at organic-on-metal interfaces. Using current-voltage measurements performed in vacuum, we demonstrate that carrier injection is identical from top and bottom cathodes. @FootnoteText@ @footnote 1@Role of electrode contamination in electron injection at Mg:Ag/Alq@sub 3@ interfaces, C. Shen, I.G. Hill and A. Kahn, Adv. Mat. 11, 1523 (1999).

10:00am OF+EL+SS-WeM6 Microcontacts to Self-Assembled Monolayers with a Conducting AFM Tip, D.J. Wold, C.D. Frisbie, University of Minnesota

Molecular level electrical transport studies require innovative approaches for making electrical contacts to oriented molecules. While scanning tunneling microscopy (STM) and electrochemical methods have been used for years to study transport in surface-confined molecules, conducting probe atomic force microscopy (CP-AFM) provides an alternative approach to electrically contacting monolayer films and the formation of metalmolecule-metal junctions. In CP-AFM, a metal-coated AFM tip is placed in direct contact, under controlled load, with the material to be probed. The technique differs from STM in that the probe is positioned using normal force feedback, which decouples probe positioning from electrical measurements. Using this technique, we show that CP-AFM may be used to make mechanically stable electrical contact to SAMs of alkane thiols on Au. We have probed the current-voltage (I-V) characteristics of the resulting junctions as a function of the number of methylenes in the alkane chains and the load applied to the tip-sample contact. The ease of this technique and the fine control of the probe during measurements make CP-AFM a promising approach for studying transport through molecular junctions. Further studies of dependence on conjugation, functional group distributions, orientations, and molecular dimensions will also be discussed.

10:20am OF+EL+SS-WeM7 White-Light-Emitting Organic EL Devices Based on Vacuum Deposited Thin Films, J. Kido, Yamagata University, Japan INVITED

In this paper, we describe the design and fabrication of bright and high efficiency white-light-emitting EL devices based on vacuum deposited organic thin films. In order to archive high quantum efficiency, multilayer structures are employed. White light can be generated by using two emitter layers composed of blue and yellow emitters. For the blue emitter layer, distyrylbiphenyl derivative is doped with a few percent of distyrylarylene derivative with carbazolyl groups. For the yellow emitter layer, rubrene was doped into hole-transporting arylamine derivative (NPD). Reduction of drive voltage was realized by using metal-doped electron injection layer,@footnote 1@ which is composed of electrontransporting bathophenantroline (Bphen) doped with Cs metal. Cs-doping to Bphen reduces resistivity of the Bphen film, and the contact between cathode and the Bphen layer becomes ohmic, which results in the low drive voltage. The typical device structure is ITO/NPD/yellow-emitting layer/blue-emitting/Bphen doped with Cs/Al. By optimizing the thickness of each layer and dopant concentration, the white EL devices exhibited extremely high luminous efficiency of 15 lm/W and external quantum efficiency of 4% which are the highest values reported for white organic EL devices. @FootnoteText@@footnote 1@J.Kido and T.Matsumoto, Apply. Phys. Lett, 73, 2868(1998).

Organic Films and Devices Room Exhibit Hall C & D - Session OF-WeP

Poster Session

OF-WeP1 Electrical Properties of Polyvinylidene Fluoride Films Prepared by Physical Vapor Deposition Method, *G.B. Park*, Yuhan College, Korea; *M.Y. Chung, S.W. Lee, S.H. Park, D.C. Lee*, Inha University, Korea

Poly Vinylidene Fluoride thin films were prepared by using a physical vapor deposition and high electric field applying method. Thin films were studied with DSC, FT-IR, X-ray diffraction and electrical conduction measuring system. The melting point of PVDF thin film increases with increasing substrate temperature. It is identified by FT-IR that the crystalline phase of @alpha@ type PVDF is transformed to @beta@ type with increasing electric field applied during preparation. It is found that the crystallinity of PVDF thin films increases from 49.8% to 67% with increasing substrate temperature from 30 to 80. The absorption current of @alpha@ type PVDF increases with increasing the electric field applied under measurement and the current increment of @beta@ type is higher than that of @alpha@ type. The ion hopping distance, derived from a relation between current density and measuring temperature, increases from 51.5 Å to 153.5 Å with increasing temperature. From above results, the conduction mechanism of PVDF thin film is estimated as ionic.

OF-WeP2 Transport Gap and Polarization Energy at Metals (Ag, Au) -Organic Molecular Semiconductor PTCDA Interfaces, *W. Gao, A. Kahn,* Princeton University

The complexity of localization and polarization in molecular solids demands experimental determination of more reliable energy diagrams for charge carrier injection and transport phenomena than just from optical measurements. We use inverse photoelectron spectroscopy (IPES) and ultraviolet photoelectron spectroscopy (UPS) to investigate unoccupied and occupied electronic states of PTCDA (3,4,9,10 - perylenetetracarboxylic dianhydride) deposited on Ag. The interface shows metal-to-organic charge transfer and formation of polaron states. The relative shifts of the vacuum level and molecular levels were analyzed in the context of interface dipole model, extended to account for the evolution of polarization energy. The comparison between the splitting of the highest occupied and lowest unoccupied molecular orbitals (HOMO and LUMO) measured via UPS and IPES, and the optical gap measured via absorption measurements leads to an estimate of exciton binding energy E@sub e-h@ to be large (0.6eV), in accordance with the highly correlated nature of this molecular solid. We also use scanning tunneling microscopy (STM) and spectroscopy (STS) for PTCDA deposited on Au(111), and find results consistent with the UPS/IPES results. Work is supported by the National Science Foundation (DMR-98-09483).

OF-WeP3 Controlled Doping of Polycrystalline and Amorphous Molecular Organic Layers: Physics and Device Prospects, X. Zhou, B. Maennig, M. Pfeiffer, J. Blochwitz, T. Fritz, K. Leo, TU Dresden, Institut fuer Angewandte Photophysik, Germany

Organic dyes with a conjugated electron system are currently investigated intensively for optoelectronic applications. In contrast to classical silicon technology, the materials used for both research and devices such as organic light-emitting diodes (OLED) are usually prepared in a nominally undoped form, leading to scattering of device parameters and higher operating voltages as compared to e.g. polymeric devices. Shifting the Fermi level towards the transport states by doping can reduce ohmic losses, ease carrier injection from contacts and increase the built-in potential of Schottky- or pn-junctions. We present here the results of a comprehensive study of controlled p-type doping of various polycrystalline and amorphous organic materials by the strong organic acceptor F4-TCNQ (tetrafluoro-tetracyano-quinodimethane). It turns out that doping is more efficient for the polycrystalline materials like the phthalocyanines where doping enhances the conductivity by up to eight orders of magnitude (10@super -2@ S/cm). Nevertheless, we could show for the first time that also amorphous phthalocyanine layers (deposited onto cooled substrates) and amorphous wide-gap materials can be doped, i.e. their conductivity increases and their Seebeck coefficient decreases indicating a shift of the Fermi level towards the hole transport state. Amorphous wide gap materials like TDATA or TPD are commonly used as hole transport materials in OLEDs because they form smooth and stable layers. We show here that controlled intentional doping of these layers strongly reduces the operating voltages of OLEDs.

OF-WeP4 Cascade-Like Hybrid Organic-CdS Quantum Particle Architectures Studied by the Attenuated Low Energy Photoelectron Spectroscopy, A. Samokhvalov, M. Berfeld, M. Lahav, R. Naaman, Weizmann Institute of Science, Israel; E. Rabani, Tel Aviv University, Israel Hybrid organic/inorganic matrices containing CdS quantum particles (QP) arranged in periodic layers separated by bilayers of arachidic acid/thioarachidic acid were prepared by Langmuir-Blodgett deposition on gold substrate. Within each layer, the QP are of the same average size of about 2.5 or 5nm, and the layers are arranged in cascade-like pattern. Electronic properties of the structures above were studied by the Attenuated Low Energy Photoelectron Spectroscopy in which a "pump" laser excites QP and a "probe" laser ejects photoelectrons either from gold or from the QP. This spectroscopy provides detailed information on electronic states of the QP and shows that they depend on the specific organization of the QP within the matrix, as well as on the interaction of the QP with the underlaying gold substrate.

OF-WeP5 Photoemission Investigation of Metal/CuPc Interfaces, *L. Yan*, *Y. Gao*, University of Rochester; *M.G. Mason*, *C.W. Tang*, Eastman Kodak Company

Metal/organic interface play an important role in organic light emitting diodes (OLED), which has been a very active field in the past few years because of their scientific and commercial significance. Copper phthalocyanine (CuPc) has been found to improve the electron injection when it is inserted as a buffer layer between the metal cathode and Tris(8hydroxyguinoline) aluminum (Alg@sub 3@), the mostly used light emitting material in OLED. It is intriguing that CuPc, traditionally used as a hole transport material in OLED, can enhance electron injection at the cathode. To address this question, we investigated the formation and the energy level alignment at the interface between metals and CuPc, using X-ray and ultraviolet photoelectron spectroscopy (XPS and UPS) simultaneously. We found that unlike many other organic materials, CuPc has two components in C1s, whose relative intensity varies as the interface formation progresses. This property provides a unique avenue to determine the charge transfer, dipole formation and energy level alignment at the interface.

OF-WeP6 Photoemission Investigation of Energy Level Alignment and Chemistry in Al/CsF/Alq@sub 3@ Interfaces, L. Yan, Y. Gao, University of Rochester; M.G. Mason, C.W. Tang, Eastman Kodak Company

Organic light emitting diode (OLED) have attract great attention in recent years since the discovery of Tris(8-hydroxyquinoline) aluminum (Alg@sub 3@) based devices. One surprising discovery is that certain kind of metal/salt complex such as Al/LiF forms excellent cathode for electron injection, which is comparable in device performance to those made from low work function metal such as Li and Ca. However, Li has very small X-ray photoelectron spectroscopy (XPS) cross section, making it hard to investigate any possible interface chemistry. We have investigated the interface formation and energy alignment between AI/CsF and Alq@sub 3@, using ultraviolet photoelectron spectroscopy (UPS) and XPS simultaneously. The experiment result indicates that charge transfer to Alq@sub 3@ had occurred at the Al/CsF/Alq@sub 3@ interface, similar to Al/LiF/Alq@sub 3@ interface. While there is no reaction is detectable by photoemission between Al and LiF, there are significant changes in core level spectra between Al and CsF. On the other hand, the energy level alignment for the two systems is strikingly similar, which is consistent to the device performance studies. Based on these observation and simplified thermodynamic calculation, possible decomposition is proposed at the Al/LiF(CsF)/Alg@sub 3@ interfaces.

OF-WeP7 Scanning Tunneling Microscopy and X-ray Photoelectron Spectroscopy of Metal(Au,Ag) Deposited Alkanethiol and Alkanedithiol Layers, T. Ohgi, W.-L. Deng, D. Fujita, H. Nejoh, National Research Institute for Metals, Japan

The self-assembled monolayers (SAMs) of thiol molecules on Au(111) substrates have been extensively studied because of their easy preparation and potential for many applications. For example, in nano-electronics studies, application of the SAMs as a tunneling barrier@footnote 1@ is one of the attractive candidates since it is very easy to obtain widely spread, densely packed, well ordered and atomicaly flat surface and moreover, the thickness of the SAMs can be easily and exactly controlled by changing the length of the molecules. Electrical property of SAMs has so far been investigated by using a metal/SAMs/metal heterostructure, and their structural analysis has been mainly carried out by XPS, UPS, and ISS.@footnote 2@ In the previous study,@footnote 3@ we reported that in the case of SAMs of thiol molecules (HS(CH@sub 2@)@sub n-

1@CH@sub 3@: C@sub n@S), evaporated gold atoms penetrate through the SAMs. They cannot support metal overlayers, but monoatomic-height Au islands grow at the interface of the Au(111) substrate and SAMs. On the other hand, in the case of dithiol (HS(CH@sub 2@)@sub n@SH: C@sub n@S@sub 2@)layers, small Au particles are formed on them. In this paper, we show the result of Ag deposited octanethiol SAMs and alkanedithiol layers and discuss the difference from Au deposited ones. Ag atoms penetrate through both layers and do not form particles on them. The temporal change of Au particles/alkanedithiol/Au(111) structure were also studied. Sequential observation shows that particles penetrate through layers in weeks and form monatomic height islands under layers. @FootnoteText@ @footnote 1@ R. P. Andres, et. al., J. Vac. Sci. Technol. A14,(1996) 1178 @footnote 2@ D. R. Jung, et.al., J. Vac. Sci. Technol. A14,(1996) 1779 @footnote 3@ T. Ohgi, H. -Y. Sheng, H. Nejoh, Applied Surface Science 130-132, (1998) 919, T. Ohgi, H. -Y. Sheng, Z. -C. Dong, H. Nejoh, Surface Science 442, (1999) 277.

OF-WeP8 Wavelength- and Time-Dependent Two-Photon Photoemission Spectroscopy of the Dye Coated Silicon Surface, A. Samokhvalov, R. Naaman, Weizmann Institute of Science, Israel

Two dye molecules of similar structure, Rhodamine B and Sulforhodamine, were adsorbed on n- and p-doped silicon. The effect of photoexcitation of the adsorbed species on electronic properties of the surface of silicon was investigated applying the Wavelength- and Time-Dependent Two-Photon Photoemission Spectroscopy (WD-TPPE). It was found that the adsorption of Sulforhodamine, but not of Rhodamine B, causes a decrease in workfunction. For both dyes, the photoemission from the dye-covered silicon is reduced upon photoexcitation. The time-dependent recovery of the photoemission gets shorter for Sulforhodamine and longer for Rhodamine B, compared to the non-covered silicon. These observations are explained based on the electron donating properties of the molecules. In the case of Rhodamine B, photoexcitation of less than 10@super-4@ of the molecules on the surface was enough to affect the photoemission yield.

OF-WeP9 Structure and Molecular Recognition Ability of Thiolatedcyclodextrin Monolayer on Au(111) Surface, *S. Yasuda*, University of Tsukuba, Japan; *I. Suzuki*, Tohoku University, Japan; *K. Yase*, National Institute of Materials and Chemical Research, Japan; *J. Sumaoka*, *M. Komiyama*, University of Tokyo, Japan; *H. Shigekawa*, University of Tsukuba, Japan

Chemisorbed monolayers of thiols and disulfides on gold, so-called selfassembled monolayers (SAMs), have been studied to develop the novel interfacial systems. Since they easily form stable and highly packed monolayers, they are considered to have high potential to fabricate the micro-morphology of materials. From the point of view to develop a molecular recognition sensor using this technique, we analyzed structure and molecular recognition ability of the LP-@beta@-CyD (@beta@cyclodextrin modified with lipoamide residue) monolayers formed on Au(111) surfaces, by using scanning tunneling microscopy (STM) and cyclic voltammetry (CV) measurement. The detailed adsorption process was completely different from that predicted from the macroscopic analyses. According to the macroscopic analysis, the growth process was explained by the Elovich model, which is based on the repulsive interaction between adsorbed molecules. However, many island structures were formed with the immersion time, indicating that the interaction between LP-@beta@-CyD molecules is attractive. Although the structure of the LP-@beta@-CyD molecules in the adsorbed layer was disorder, formation of the monolayer structure was clearly shown by STM. In order to examine the molecular recognition ability of the LP-@beta@-CyD/Au(111), we performed CV measurement using two electroactive makers; ferrocenecarboxylic acid (FCA) and hexacyanoferrate (HCF). FCA molecules can be included into @beta@-CyD cavity, but HCF molecules can not be. Therefore, if the monolayer structure is densely formed with the CyD cavity being perpendicular to the surface, the oxidation-reduction current is expected to be observed only for the case of the FCA molecules, which in fact was clearly shown by our experiment. These results indicate that the LP-@beta@-CyD/Au(111) structure has high potential as a novel molecular recognition sensor with its selective permeability. http://dora.ims.tsukuba.ac.jp Appl. Phys. Lett., 76 (2000).)

OF-WeP10 Growth Modes of Vacuum Evaporated Pentacene on SiO2, MoS2 and Au Substrates, S. Zorba, Q.T. Toan, N.J. Watkins, Y. Gao, University of Rochester

Pentacene is one of the most widely used active material in organic thinfilm transistors because of its remarkably high mobility. We studied the growth modes of vacuum evaporated pentacene on SiO2, MoS2 and Au substrates using Atomic Force Microscopy. Pentacene films were grown side by side on SiO2 and MoS2 substrates and separately on Au substrate by vacuum evaporation at room temperature with a deposition rate of 0.6 @Ao@/s. Pentacene films grow on SiO2 substrate in a layer by layer manner with full coverage at average thickness of 20 @Ao@ and have the highest degree of molecular ordering with large dendritic grains among the three materials. Films grown on MoS2 substrate reveal two different growth modes, ice-flake like growth and granular growth, both of which seem to compete with each other. On the other hand, films deposited on Au substrate show granular structure.

OF-WeP11 Analysis of the Surface Morphology of the Initial Growth Layers of p-quaterphenyl on NaCl (001), *E.J. Kintzel, Jr.*¹², *E.A. Akhadov, T.W. Trelenberg, J.G. Skofronick, S.A. Safron, D.H. Van Winkle,* Florida State University; *F. Flaherty,* Valdosta State University; *D.-M. Smilgies,* European Synchrotron Radiation Facility

We have investigated the structural properties of the initial growth layers of p-quaterphenyl (p-4P) vapor deposited on NaCl (001) using Atomic Force Microscopy (AFM), Helium Atom Scattering (HAS), and X-Ray Grazing Incidence Diffraction (GID). The series of AFM studies provides evidence of needle-like accumulations of p-4P nucleating around surface defects, a striped-phase region with a lateral spacing of approximately 25 nm, and a region which displays a transition from lying to standing orientation of the molecules. HAS investigations at ~50K for films grown at 200K reveal many diffraction peaks which do not appear at the higher temperature. The helium diffraction pattern suggests the formation of randomly oriented micro-crystallites. Our GID studies indicate self-assembly of oriented crystallites in thin films. In thicker samples the diffraction becomes isotropic, like a powder pattern, indicating a random distribution of crystallite orientations.

OF-WeP12 Preparation of Stable Organic Layers Attached to Metals via a Double Bond, *H. Oudghiri-Hassani*, *M. Siaj*, *E.M. Zahidi*, *P.H. McBreen*, Laval University, Canada

New methods for preparing inorganic-organic interfaces lead to new types of functionalized surfaces. We describe a method to attach organic layers to a conducting solid via the formation of a carbon-metal double bond. The substrate is bulk molybdenum carbide, a material displaying metallic- like conductivity and ceramic-like hardness, as well as excellent catalytic activity. Early transition metal carbides are also of interest because they may form natural electrical contacts to carbon nanotubes in molecular electronics applications. The organic layers were formed by dissociatively chemisorbing carbonyl compounds on the carbide surface. By suitable preparation of the surface, and careful coverage control, layers stable to 1000 K could be prepared. The stability, structure and reactivity of these unprecedently stable layers were evaluated using several surface spectroscopies.

Semiconductors

Room Exhibit Hall C & D - Session SC+EL+SS-WeP

Poster Session

SC+EL+SS-WeP1 Selectivity in Attachment of a Model pi-conjugated Organic Molecule to a Group IV Semiconductor Surface: Styrene on Si(001), *M.P. Schwartz*, University of Wisconsin, Madison; *M.D. Ellison*, Wittenberg University; *S.K. Coulter, R.J. Hamers*, University of Wisconsin, Madison

The bonding of styrene to the Si(001) surface has been investigated as a model system for understanding selectivity in the attachment of conjugated pi-electron systems to semiconductor surfaces. Scanning tunneling microscopy images show one primary bonding configuration, slightly off-center from the middle of a dimer row. Infrared spectra using isotopically-labeled styrene establish that attachment occurs in a highly selective way, bonding through the external vinyl group and leaving the aromatic ring almost completely unperturbed. The implications for the high degree of selectivity in understanding attachment of other conjugated pi-electron systems are discussed.

¹ Morton S. Traum Award Finalist ² NSTD Student Award Finalist

SC+EL+SS-WeP2 Ferrocene and Decamethylferrocene Adsorption and Decomposition on Ag(100) and Si(111), *C.M. Woodbridge*, *D.L. Pugmire*, University of Nebraska, Lincoln; *N.M. Boag*, University of Salford; *M.A. Langell*, University of Nebraska, Lincoln

Although metallocenes show potential as Chemical Vapor Deposition (CVD) source molecules, there is comparatively little known about their interactions with oriented substrates. We have investigated the adsorption and decomposition of ferrocene (FeCp@sub 2@) and decamethylferrocene (FeCp@sub 2@*) on Ag(100) and Si(111) using High Resolution Electron Energy Loss Spectroscopy (HREELS), Temperature Programmed Desorption (TPD), and X-ray Photoelectron Spectroscopy (XPS). For weakly-interacting systems such as those which occur with Ag(100), both FeCp@sub 2@ and FeCp@sub 2@* are adsorbed molecularly at 130 K. Monolayers of both FeCp@sub 2@ and FeCp@sub 2@* are oriented such that their molecular axes are perpendicular to the plane of the Ag(100) substrate; monolayer desorption occurs at approximately 250 K for both metallocenes. While FeCp@sub 2@ desorption is clean, FeCp@sub 2@* shows significant amounts of metallocene dissociation competing with molecular desorption. The Si(111)/metallocene systems also show molecular adsorption at 130 K but are more reactive to thermal decomposition upon heating and decompose primarily through hydrogenation and ligand-metal dissociation mechanisms. Specific information about the orientation of the adsorbed species and decomposition intermediates will be discussed.

SC+EL+SS-WeP3 Lowering of Processing Temperature due to a High Pressure Deuterium Anneal for Improved CMOS Hot Carrier Reliability, J. Lee, K. Cheng, K. Hess, J.W. Lyding, University of Illinois, Urbana; Y.K. Kim, Y.W. Kim, K.P. Suh, Samsung Electronics Co., Ltd.

The deuterium (D) isotope effect has been found to be very effective in reducing hot carrier induced degradation in CMOS transistors of numerous technologies. The magnitude of lifetime improvement (10x to 100x) varies from one technology to the other, but it directly correlates with D incorporation at the gate SiO@sub 2@/Si interface. Secondary ion mass spectrometry (SIMS) depth profiling has been used to make this determination. We have recently implemented high pressure D annealing to enhance its incorporation at the interface. By increasing the D pressure, the concentration at the interface can be increased for a fixed annealing temperature. Consequently, lower temperatures and shorter anneal times can achieve equivalent transistor reliability. This promises to be a technologically significant result for future CMOS production which requires a much lower thermal budget process due to the introduction of advanced materials (e.g. low k dielectrics) and increased number of metal layers. This high pressure annealing technique has been applied to one of the most recent CMOS technologies from Samsung Electronics. For these short-channel (0.18 µm) and low operating voltage (1.5V) devices, the isotope effect is substantially enhanced (700x). Rather than being scaled away, deuterium reduction of hot electron damage appears more relevant in future generations of CMOS integrated circuits. In the current work, the annealing temperature has been lowered from 450@degree@C to 350@degree@C. Although the lifetime improvement is not as great, we do observe a significant lifetime improvement (300x) just from changes in pressure. More experiments are in progress to maximize the D incorporation at the low annealing temperature. In addition, SIMS depth profiles are being determined for devices that were sintered at different annealing conditions.

SC+EL+SS-WeP4 Investigation of the Penetration of Atomic Hydrogen from the Gas Phase into a SiO@sub 2@/GaAs System, V.A. Kagadei, Research Institute of Semiconductor Devices, Russia; E.V. Nefedtsev, Tomsk University of Control Systems and Radioelectronics, Russia; D.I. Proskurovsky, Institute of High Current Electronics, Russia

Introduction of hydrogen into near-surface layers of semiconductor materials (hydrogenation) substantially varies their properties. In some cases hydrogenation improves the electrophysical parameters of the material and allows one to create devices with improved characteristics, while in other cases the penetration of hydrogen into a solid accompanies a technological process and causes unwanted changes in the parameters of the material. Therefore, it appears urgent to investigate the penetration of hydrogen into a semiconductor material, and a better understanding of this process will make it possible to optimize the technology of hydrogenation. The hydrogenation of GaAs samples coated with thin (5 nm) SiO@sub 2@ film was investigated. Samples were treated in a flow consisting of a mixture of atomic and molecular hydrogen produced by a source whose operation is based on a reflected arc discharge with a hollow cathode and a self-heating element. The hydrogenation time was 5 - 30 min, the hydrogenation temperature was 150 - 300 C, and the hydrogen pressure

was varied from 10@super -1@ - 10@super -3@ Pa. It has been established that an increase in discharge current results in an increase in the concentration of atomic hydrogen in the gas phase, N, and in a decrease in the number of atoms penetrating into samples, and this is in contradiction with the usual notions about the penetration of hydrogen atoms into a solid. The data obtained suggest that the amount of hydrogen penetrating into samples is more dependent on the probability of the penetration of hydrogen atoms into a solid body, F, rather than on N. It has been proposed that F decreases substantially with decreasing the energy of the hydrogen atoms arriving at the solid surface. The energy of the atoms emerging from the reflected-arc-discharge-based source is estimated to vary between 0.1 and 10 eV. It is determined by the operating voltage of the discharge and decreases with increasing discharge current. Another possible cause of the observed phenomena is the formation of a nearsurface diffusion barrier constituted by immobile hydrogen molecules, which occupy interstitials and retard the diffusion of atoms. The contribution of each of the proposed mechanism is discussed.

SC+EL+SS-WeP5 a-SiC:H Thin Films Fabricated by the High Rate Deposition Method, B.G. Budaguan, A.A. Sherchenkov, Moscow Institute of Electronic Technology, Russia; A.A. Berdnikov, V.D. Chernomordic, Institute of Microelectronics of Russian Academy of Science; A.A. Aivazov, UniSil Corp. The a-SiC:H alloys are considered to be a perspective wide band gap material for different optoelectronic utilization. For the commercial application it is necessary to increase the deposition rate. However the increase of the growth rate results in the increase of structural inhomogeneity and in the deterioration of electronic properties of amorphous layers. Recently we have shown that deposition rate of a-Si:H films with high electronic properties can be increased with using of low frequency (55 kHz) glow discharge. In this work we investigated the growth mechanism and microstructure of a-SiC:H thin films fabricated for the first time by this method. The a-SiC:H films were deposited at different methane content from 0 to 100%, substrate temperatures T@sub s@ from 160 to 320 °C, and different discharge regimes: continuous wave and square wave modulated (SQWM). It was shown that the increase of the deposition rate of a-SiC:H films (5.3-11.1 Å/s depending on the methane content in gas mixture) in comparison with the standard deposition technology (3 Å/s for 13.56 MHz PECVD) is caused by the close position of a-SiC:H precursors formation to the growth surface. The joint analysis with using of infrared/optical spectroscopy and atomic force microscopy measurements showed that a-SiC:H films has the island type microstructure where the clustering of C atoms occurs at the island surfaces in the form of C-H@sub n@ bonds. The increase of C-H@sub n@ configurations on islands surfaces at high C content facilitate the relaxation of rigid a-SiC:H network through formation of flexible sp@super 2@-sites. The incorporation of Si-C bonds in the interior of islands determines the optical bandgap while the clustering of CH@sub n@ and SiH at the islands surface leads to the formation of graphite-like microstructure. It was shown that the suppression of formation of graphite-like microstructure at low T@sub s@ and in SQWM plasma allows to fabricate device quality allovs.

SC+EL+SS-WeP6 Mechanism for and Site of the Dissociative Chemisorption of XeF@sub 2@ on Si(100)2x1 Below 1 ML of Fluorine Coverage, J.R. Holt, R.C. Hefty, M.R. Tate, S.T. Ceyer, Massachusetts Institute of Technology

Upon exposure of a clean Si(100)2x1 reconstructed surface to a beam of xenon difluoride incident with an average kinetic energy of 0.9 kcal/mol, the XeF@sub 2@ dissociatively chemisorbs by atom abstraction solely on the Si dangling bonds up to a fluorine coverage of one monolayer (ML) before it begins to react with the Si-Si lattice bonds. This conclusion is based on the observations of scattered XeF and the preservation of the 2x1 dimer row reconstruction at 1 ML fluorine coverage. The scattered XeF is detected by a line-of-sight and differentially pumped mass spectrometer while the order of the surface is monitored by He diffraction. A clean Si(100)2x1 surface is characterized by three primary features in a He diffraction spectrum: a specular feature due to the smoothness and general order of the surface, a half-order feature due to diffraction perpendicular to the dimer rows, and a first order feature due to diffraction parallel to the dimer rows. The presence of the half-order feature at a fluorine coverage of 1 ML provides evidence that even the Si-Si sigma dimer bonds are undisturbed, preserving the original dimer rows. The reaction exothermicity of approximately 230 kcal/mol does not destroy the surface order. Molecular fluorine has previously been observed to react with a clean Si(100)2x1 surface in a similar manner by atom abstraction, saturating the Si dangling bonds at a coverage of 1 ML. The 2x1 periodicity

Wednesday Morning Poster Sessions, October 4, 2000

is maintained. However, after saturation of the dangling bonds, F@sub 2@ ceases reacting with the surface while XeF@sub 2@ continues to deposit fluorine on the surface by its reaction with the Si-Si sigma dimer bonds and the Si-Si lattice bonds. The surface order is destroyed as a result of the continued fluorine deposition and ultimately etching occurs by the formation of volatile SiF@sub 4@.

SC+EL+SS-WeP7 STM Investigations of the Initial Ad- and Desorption Sites of Molecular Hydrogen on Si(001), *M. Dürr*, Philipps University Marburg, Germany; *A. Biedermann, Z. Hu*, Columbia University; *U. Höfer*, Philipps University Marburg, Germany; *T.F. Heinz*, Columbia University

Whereas the extremely small sticking coefficients for dissociative adsorption of H@sub 2@ on Si surfaces indicate a high, the almost thermal energy distribution of the desorbing H@sub 2@ molecules points to a low barrier in the reaction channel. Recent molecular beam experiments have shown that this apparent contradiction is in full accordance with the principle of detailed balance and can be understood in terms of phononassisted sticking.@footnote 1@ To shed light on the underlying microscopic mechanisms, we have adsorbed H@sub 2@ on Si(001) at temperatures below the onset of H diffusion and investigated the site distributions with scanning tunnelling micrcoscopy (STM). The STM images show configurations of 4 adsorbed H atoms indicating a two-step process with an inter-dimer rather than the commonly assumed intra-dimer adsorption path as the relevant initial step. In the inter-dimer path, H@sub 2@ interacts with two dangling-bonds on adjacent Si dimers and forms a transition state with relatively large lattice distortion. Single-shot laserinduced thermal desorption experiments from nearly perfect hydrogen monolayers reveal distributions of unsaturated dangling bonds which indicate that the reverse path is also active in desorption. The influence of coverage, minority reaction channels as well as the consequences of the results on the reaction kinetics will be discussed. @FootnoteText@ @footnote 1@ M. Dürr, M. B. Raschke, and U. Höfer, J. Chem. Phys. 111, 10411 (1999).

SC+EL+SS-WeP8 Photoemission Study on Initial Oxidation of Si(001) Surfaces with Supersonic O@sub 2@ Molecular Beams, Y. Teraoka, Japan Atomic Energy Research Institute, Japan; A. Yoshigoe, Japan Atomic Energy Research Institute

We made a new surface reaction analysis apparatus at a soft x-ray beamline (BL23SU) in the SPring-8 (Super Photon ring-8GeV) to study incident energy effects for reactant chemisorption on semiconductor surfaces. As the first step, initial oxidation of Si(001) with O@sub 2@ has been investigated because that is not only interesting for surface reaction analysis but also important as electronic device development. The maximum incident energy was 3 eV in calculation. The clean Si(001) surfaces were irradiated by the supersonic O@sub 2@ molecular beams with various incident energy to achieve saturated adsorption. The oxygen amount on the surface was evaluated by measuring O-1s photoemission intensity. The intensity depended on the incident energy and two thresholds of 1.0 eV and 2.6 eV were found. These values are very resemble to the predicted values of 0.8 eV and 2.4 eV from the firstprinciples calculation, showing potential energy barriers for dimer backbond oxidation and oxygen insertion between the second and the third layer. Si-2p photoemission spectra were obtained at room temperature and 873 K by using high resolution soft x-rays from the beamline. In the case of room temperature, the maximum silicon oxidation number increased with increasing the incident energy from Si@super 2+@ to Si@super 4+@. Whereas a peak corresponding to SiO@sub 2@ was minor even in the case of 2.9 eV at room temperature, the peak was apparent in 873 K cases. Thermal energy may drive oxygen migration to form the SiO@sub 2@ structure. Even at such high temperature, incident energy affected in sub-oxide peak composition. The sub-oxide peak for Si@super 3+@ was increased with increasing the incident energy and was dominant in the case of 2.9 eV whereas the peak for Si@super 2+@ was primary in the case of 0.6 eV. The variation may be resultant from the Si@super 3+@ increase due to oxidation of dimer and sub-surface silicon atoms depending on the incident energy.

SC+EL+SS-WeP9 The Effect of Time and Moisture on the Adhesion Bond between Silica Particle and Silicon Oxide Substrate, J.W. Feng, A.A. Busnaina, Clarkson University

Adhesion of silica particles to silicon wafers is a problem that affects semiconductor manufacturing processes. The particle adhesion forces are greatly affected by the environment such as humidity, temperature and adhesion induced stress between the particle and the wafer following the particle deposition. The adhesion forces considered in the process include van der Waals, capillary force, double layer force and hydrogen bonding. In this study, silica particles are deposited onto wet and dry thermal oxide silicon wafers, then the samples are aged in different relative humidity environments. Results show that the largest increase in contact area between silica particles and thermal oxide wafers occur when the particle is first deposited on wet surface then aged in relative humidity above 55%. Higher humidity, results in higher adhesion force and lower removal efficiency. Results also indicate that adhesion force increases by more than two order of magnitude after the aging process. This suggests that hydrogen and covalent bonds are responsible for the increase in the adhesion force especially in humid environments.

SC+EL+SS-WeP10 Influence of Growth Direction on Order-Disorder Transition in (GaAs)@sub (1-x)@(Ge)@sub 2x@ Semiconductors, A.G. Rodriguez, H. Navarro-Contreras, M.A. Vidal, University, Mexico

We provide direct evidence of the dependence on the growth direction of the critical concentration of IV atoms at the order-disorder transition in ternary metastable (III-V)-IV, zincblende-diamond semiconductor alloys. The excellent agreement between the experimental and model predicted critical concentrations is evidence that the atomic ordering in these alloys is ruled almost entirely by substrate geometry. We report the observation of the critical concentration dependence on substrate orientation in (GaAs)@sub (1-x)@(Ge@sub 2@)@sub x@ metastable alloys, epitaxially grown on (001), (111), (112) and (113) GaAs. A different long-range order parameter behavior with Ge concentration is obtained for each growth direction, 0.36, 0.96, 0.59, and 0.50 ± 0.03, respectively, numbers that compare well with results of a Montecarlo simulation of the growth, 0.33, 1.0, 0.64 and 0.54, respectively.

SC+EL+SS-WeP11 Surface Electronic Structure of p-type GaN(000-1), P. Ryan, Y.C. Chao, K.E. Smith, Boston University

Our investigation sought to describe the surface electronic characteristics of MBE grown (Mg-doped) wurtzite p-GaN (0001'). Four surface bands were mapped within the surface Brillouin zone. The peaks have been removed by atomic hydrogen exposure and three of the peaks show pz orbital configuration, the fourth an s orbital. The most interesting peak is a highly dispersing surface state which sweeps from the bulk valence band into the forbidden bulk band gap, approaches the Fermi level then returns to the bulk valence band. We compare this state to previously predicted mid-gap surface states.

SC+EL+SS-WeP12 Ultrafast Dephasing of Coherent Phonons by Lattice Defects in n-GaAs, *M. Kitajima*, *M. Hase*, *K. Ishioka*, National Research Institute for Metals, Japan; *K. Ushida*, RIKEN, Japan

GaAs is a key material for ultrafast switching and THz radiation because the carrier lifetime of low-temperature grown (defective) GaAs is ultrafast (sub-picosecond). In doped GaAs, the plasmon and the LO phonon form coupled modes through Coulomb interactions, and the frequencies of the LO phonon-plasmon coupled (LOPC) modes depend on the carrier density. We report the effect of active lattice defects on dephasing of coherent LOPC modes in He-ion irradiated n-GaAs by using a femtosecond pumpprobe technique. The time-domain oscillations of the coherent LOPC modes in He@super +@ irradiated n-GaAs have been precisely measured for the different ion doses. The samples used were n-type GaAs with carrier density of ndop= 1.4x10@super 18@cm@super -3@. In order to examine the effect of point defects, 5 keV He@super +@ were irradiated to n-GaAs samples at doses of 9.4x10@super 12@ and 3.0x10@super 14@ He@super +@/cm@super 2@ in a UHV chamber with base pressure of 3x10@super -9@ Torr. The light source was a mode-locked Ti:sapphire laser with a pulse width of 25 fs. The anisotropic reflectivity change revealed coherent oscillations which shows beating pattern for the asgrown n-GaAs. This beating pattern in the time-domain data is due to an existence of the strong LO mode and the L@sub -@ mode. The mode beating changed clearly as increasing the ion dose, and the pattern of the Lmode disappeared at doses higher than 3.0x10@super 13@ He@super +@/cm@super 2@. The results suggest that defect-induced carrier trapping dominate annihilation of the coherent coupled modes. In addition we will also discuss on an anormalous behavior of dephasing of the coherent LO-phonon.

SC+EL+SS-WeP13 High Density Plasma Via Hole Etching In SiC, H. Cho, Miryang National University, South Korea; K.P. Lee, P. Leerungnawarat, University of Florida; S.N.G. Chu, Lucent Technologies, Bell Laboratories; F. Ren, University of Florida; C.-M. Zetterling, Royal Institute of Technology (KTH), Sweden; S.J. Pearton, University of Florida

Through-wafer vias ~100µm deep were formed in 6H-SiC substrates by Inductively Coupled Plasma etching with SF@sub 6@/O@sub 2@ at rates up to 0.8 µm·min@super -1@ and employing Al masks. Selectivies of @>@40 in SiC over Al were achieved. Electrical (C-V, I-V) and chemical (AES) analysis techniques showed that the etching produced only minor changes in reverse breakdown voltage, Schottky barrier height and nearsurface stoichiometry of the SiC and had high selectivity over common front side metallization. The SiC etch rate and etch yield were measured as a function of plasma composition along with the selectivity over Al. This process is attractive for power SiC transistors intended for high current, high temperature applications.

SC+EL+SS-WeP14 RHEED Study of Ion-beam Induced Carbonization for 3C-SiC Heteroepitaxial Growth on Si(100), *N. Tsubouchi*, *A. Chayahara*, *A. Kinomura*, *Y. Horino*, Osaka National Research Institute, Japan

3C-SiC heteroepitaxial film formation on a Si substrate is a very important when we consider compatibility with the silicon fabrication technology. So far, it has been reported that a carbonization process as buffer layer formation using various film-growth methods is effective for the heteroepitaxial film growth of 3C-SiC on Si while the lattice mismatch between 3C-SiC and Si is as large as 20 %. These methods reported for this reaction process, however, require high-temperatures ranging 700--1000°C, causing serious problems of redistribution of dopants and crystal defects such as dislocations and stacking faults especially at the heterointerface. In addition, carbonization reaction between provided gases including carbon atoms and Si substrates also results in promotion of defect formation in the Si-SiC interface. For solving these problems, a newly process, that is, ion-beam induced carbonization process of Si(100) with mass-separated energetic carbon ion species (e.g., @super 12@C@super -@, @super 12@C@sub 2@@super -@, @super 12@C@super +@ ions) was tried and investigated by RHEED measurements. The kinetic energies of ions and substrate temperatures were in the range 20-1200 eV and 400-700 °C, respectively. Such energetic species have possibility to lower a growth temperature inducing a decrease in defects and dislocations at the SiC/Si interface, in comparison with conventional methods. We report on the SiC growth condition during the carbonization process, i.e., ion-beam energy and substrate temperature dependence together with structural information.

SC+EL+SS-WeP15 Auger Depth Profile Analysis: Process Window Definition of 0.2 micron Aluminum RIE Interconnections, *C. Dziobkowski*, *L. Clevenger*, IBM Corporation; *M. Honda*, Toshiba, Japan; *R. Ramachandran*, Infineon Technologies

For fabrication of devices with dimensions of less than 0.2 microns, processing requirements become more demanding. New design requirements for the 256 Mbit DRAM also have higher aspect ratios. Process temperature control becomes very important because of the effects of temperature on the RIE etch, theta-Al2Cu precipitate distribution and texture. Eventually, even the electrical properties are affected resulting in device shorts and open circuits. This paper gives a description of the methodology developed to provide Auger depth profile analysis to characterize the copper distribution in the AlCu metallurgy. Copper segregation at the Al/Ti interface also affects the RIE process etching window. The information obtained from the Auger depth profiles can be used to define a window for VLSI devices with these small dimensions.

SC+EL+SS-WeP16 Epitaxial Growth of Cubic SiC Thin Films on Silicon Using New Single Molecular Precursors by MOCVD, J.-H. Boo, S.-B. Lee, Sungkyunkwan University, Korea; K.-W. Lee, Yunsoo Kim, K.-S. Yu, S.H. Yeon, I.N. Jung, Korea Research Institute of Chemical Technology, Korea Heteroepitaxial cubic SiC thin films have been deposited on silicon substrates at temperatures in the range of 750 - 1000 ° C using newly developed single molecular precursors by MOCVD method. Singlecrystalline, crack-free stoichiometric cubic SiC films were successfully grown on both Si(001) and Si(111) substrates without surface carbonization at as low as temperature of 920 ° C with 1,3-disilabutane (DSB), H@sub 3@Si-CH@sub 2@-SiH@sub 2@-CH@sub 3@, as a liquid single source precursor which contains silicon and carbon in 1:1 ratio. Cubic SiC thin films highly oriented in the [001] direction were also obtained on Si(001) using either a liquid mixture of 1,3,5-trisilapentane (TSP), H@sub 3@Si-CH@sub 2@-SiH@sub 2@-CH@sub 2@-SiH@sub 3@, and 2,4,6-trisilaheptane (TSH) at 980 ° C or 2,6-dimethyl-2,4,6-trisilaheptane (DMTSH), H@sub 3@C-SiH(CH@sub 3@)-CH@sub 2@-SiH@sub 2@-CH@sub 2@-SiH(CH@sub 3@)-CH@sub 3@ at 950 ° C without carrier gas. These growth temperatures were much lower than conventional CVD growth temperatures, and this is the first report of cubic SiC film growth using the single molecular precursors of trisilaalkanes.

SC+EL+SS-WeP17 Optical and Contact Properties of Indium Tin Oxide on p-GaN, D.W. Kim, Y.J. Sung, J.W. Bae, G.Y. Yeom, Sungkyunkwan University, Korea; H.S. Kim, University of Strathclyde, Scotland

Because Gallium nitride(GaN) is an attractive material which has an wide direct band gap, GaN-based optoeletronic devices such as light emitting diodes(LEDs) and laser diodes(LDs) in blue and ultraviolet wavelength regions have been studied intensively and fabricated successfully. However, the contacts to GaN-based LEDs are currently made by depositing metal layers on the top of GaN-based LEDs, therefore, significant optical loss is inevitable. In this study, we applied multilayers containing transparent conducting oxide such as indium tin oxide(ITO) to p-GaN and the effect of the optically more transparent contacts to p-GaN on the electrical and optical properties were investigated. As substrates, Mgdoped p-GaN layers were used. ITO thin films were deposited on p-GaN at room temperature using an oxygen radical assisted electron beam evaporator system. To improve the contact properties to p-GaN, various ITO/very thin metal multi-layer contact systems were also attempted and their electrical, structural, and optical properties were investigated. A semiconductor parameter analyzer and a four point probe were used to measure contact and electrical properties of ITO and mutilayer films on p-GaN. X-ray diffractometry(XRD) and Auger electron spectroscopy(AES) were used to investigate the structural properties of the contact during the annealing process, and an optical spectrophotometer was used to investigate the optical properties. The deposited ITO thin films showed the optical transmittance above 80 % at 420 nm(blue) with the sheet resistance of 40 ohm/sq. With ITO contact to p-GaN alone, Schottky contacts were generally obtained. However, depending on the applied very thin metal inter-layer and followed annealing conditions, different electrical and contact properties, which could be applicable to GaN devices, were obtained.

SC+EL+SS-WeP18 Visible Emission from Electroluminescent Devices using an Amorphous AlN:Cu, Mn, and Cr Thin Film Phosphor, *M.L. Caldwell*, V.I. *Dimitrova*, *M.E. Kordesch*, *H.H. Richardson*, *P.G. Van Patten*, Ohio University

Electroluminescence (EL) studies of AIN:Cu, Mn, and Cr alternating-current thin-film electroluminescent (ACTFEL) devices were performed at 300 K. Thin films of Cu, Mn, and Cr doped AlN, ~ 200 nm thick, were grown on pdoped silicon (111) substrates using RF magnetron sputtering in a nitrogen atmosphere. A transparent layer utilizing indium tin oxide was employed as the top layer contact. A strong bluish-green emission from the AIN:Cu films was observed under reverse bias due to electron impact excitation of the Cu atoms. The emission spectrum consisted of one broad peak in the visible region of 475 nm. a strong red emission from the AIN:Mn films was observed also under reverse bias due to electron impact excitation of the Mn atoms. There were two sharp emission peaks in the visible region at 680 nm and 700 nm. Studies of incorporationg the Cr@super +3@ ion will be performed to try to overcome the charge compensation problem. Temperature-dependent cathodoluminscence (CL) and photoluminscence (PL) studies will be performed between 30 - 450 K to determine the relationship of them to the EL results and show the optimum conditions for device performance.

SC+EL+SS-WeP19 Organic Contamination Removal on Silicon Substrate by Low Temperature Remote Plasma, *H. Kang*, *H. Soh*, *H. Seo*, *Y.C. Kim*, Hanyang University, Korea; *H. Jeon*, Hanyang University, Korea, South Korea

Organic contamination on silicon substrate deteriorates the film adhesion and forms deleterious decomposition during heating process. Organic impurities absorbed on the Si substrate surface generally desorbes in the form of volatile compounds by radio frequency (RF) remote oxygen and hydrogen plasma at relatively low temperatures. In this study, organic contamination removal and Si substrate surface microroughness by RF remote oxygen and hydrogen plasma will be described. The remote plasma system and analysis systems were connected by ultrahigh vacuum transfer system to avoid recontamination such as carbon absorption in the air. Organic impurity were intentionally contaminated and removed by hydrogen and oxygen remote plasma system. Surface contamination concentration and bonding state changes were analyzed by Auger electron

spectroscopy (AES) and x-ray photoelectron spectroscopy (XPS). Surface morphology and microroughness were observed by scanning tunneling microscope (STM) and atomic force microscope (AFM). After remote hydrogen and oxygen plasma cleaning, carbon impurity was significantly reduced below detection limit of AES and the Si-C peaks of XPS were not observed. The surface microroughness generally degraded with increasing plasma power and exposure time.

SC+EL+SS-WeP20 Studies of the Surface Morphology, Chemical and Structural Changes of Ion Bombarded Silicon Carbide, *P. McCarty*, University of Alabama, Huntsville; *C.I. Muntele*, *I. Muntele*, Alabama A&M University; *M.A. George*, University of Alabama, Huntsville; *D. Ila*, Alabama A&M University; *D.B. Poker*, *D.K. Hensley*, Oak Ridge National Laboratory

Silicon carbide is gaining increasing interest for high temperature/harsh environment applications including miniature integrated sensors. In the past few years, efforts have been made toward controlling the defects and impurification that occur during various growth and fabrication processes. This work is intended to analyze the surface damage that occurs during ion implantation of silicon carbide, and the evolution of these defects. In order to correlate the effects that surface damage has on the sensing properties of ion implantation based silicon carbide gas sensors we have characterized these sensors under various conditions. We present the results of our investigation of the morphological, electrical and spectroscopic characteristics of ion implanted silicon-face 6H-SiC. In this work we have used He, O, Pd, and Au at energies between 100 keV to 8 MeV at fluences between 1 x 1015/Cm2 to 3 x 1017/Cm2. The ion bombardments were performed at both room temperature (300oK) and at elevated temperature (773oK). Atomic force microscopy, surface potential measurements and electric field microscopy was performed before and after ion implantation, as well as after the post-implantation high temperature annealing. This study is correlated with results obtained using micro-Raman, FTIR and Rutherford Backscattering Spectrometry. @FootnoteText@ We would like to thank Dr. David Larkin, NASA Glenn Research Center. Research sponsored by the NASA Grant No. NG3-2302, and partially by the Center for Irradiation of Materials, Alabama A&M University and the Division of Materials Sciences, U.S. Dept. of Energy, at the Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U. S. Department of Energy under contract DE-AC05-00OR22725

SC+EL+SS-WeP21 Gallium Oxide Deposition and Radical Oxidation on GaAs(001)-(2x4) Investigated with STM, S.I. Yi, P. Kruse, M. Hale, A.C. Kummel, University of California, San Diego

Growth of metal oxide on GaAs with a low interface defect density is necessary for development of GaAs based metal oxide semiconductor field effect transistor (MOSFET). Vapor deposition of gallium oxide on GaAs(001) is emerging as a viable method for this objective. Using STM, we have investigated deposition of gallium oxide on GaAs(001)-(2x4) during the initial period and oxidation of the surface by atomic oxygen. Deposition of gallium oxide results in an atomically abrupt interface with the GaAs(001)-(2x4) surface, without disrupting the (2x4) surface order. In contrast, oxidation of GaAs(001)-(2x4) by atomic oxygen results in disordering of the surface characterized by formation of undimerized As surface atoms with half filled dangling bonds and As@subGa@ antisites. The stark difference in these two methods of oxide preparation has a profound implication for development of GaAs based MOSFET devices.

SC+EL+SS-WeP22 Density Functional Theory Studies of Semiconductor Surfaces, G.S. Hwang, California Institute of Technology; C.B. Shin, Ajou University, South Korea

Density functional theory (DFT) simulations have been proven to be a reliable and tractable tool in condensed matter physics. Indeed, these simulations are now successfully used to treat not only simple ordered solids but also complex systems such as surfaces and point-like/extended defects. We present the results of our recent pseudopotential based DFT studies which included: (i) the dynamics and configurations of Si(100) and (ii) the adsorption of hydrogen molecules on the surface. It is now rather well known that dimers on Si(100) are alternatively buckled at the ground state. However, the details of their geometry and dynamics at room temperature are still an issue of controversy. Our studies illustrate a tied flipping behavior of two consecutive dimers: the buckling of adjacent outer dimers becomes stronger while two inner dimers switch their orientations. Contrary to popular speculation, in most cases, the dimers undergo thermal fluctuations between two unequal energy minima, thereby preserving the 2x anticorrelation of dimer buckling along a row even at room temperature. Based upon such understanding of the dynamical behaviors of Si(100) at finite temperature, we have looked into dissociative

adsorption of H@sub 2@ on Si(100), which is still ambiguous. This study reveals that intradimer @pi@-bonding disruption caused by thermal induced dimer stretching is mainly responsible for the anomalously strong surface temperature dependence of H@sub 2@ adsorption on the clean Si(100) surface.

SC+EL+SS-WeP23 Investigation of Polycrystalline Silicon Grain Structure by Single Wafer Rapid Thermal Chemical Vapor Deposition (RTCVD), H. Bu, C. Hu, M. Bevan, L. Tsung, Texas Instruments; L. Luo, Applied Materials It is known that the grain structure in poly-Si gate electrode can directly affect dopant activation and gate electrode depletion (GED). It is highly desirable to control the grain size and orientation during processing for improved IC device yield and reliability. This paper demonstrates the capability of tuning and generating a specific poly-Si grain structure with a lamp based and a heater based single wafer rapid thermal chemical vapor deposition (RTCVD) reactor at reduced pressure regime. Nitrogen gas is used as the carrier gas. The deposition temperature is varied from 650°C to 700°C. The effect of the concentration of intentionally added hydrogen during deposition is examined. Films deposited at various process conditions are characterized by TEM and XRD analysis. The results show that poly-Si grain size and orientation are sensitive to the hydrogen concentration. With a carefully selected process temperature and hydrogen concentration combination, the RTCVD technique is able to engineer the poly-Si grain size and orientation. The effect on poly-Si grain structure on electrical parameters such as electrical oxide thickness (EOT) and gate electrode depletion (GED) will be discussed.

SC+EL+SS-WeP24 Buried Low-Temperature (T@sub s@ <500 °C) Lateral Epitaxial Overgrowth of Si on SiO@sub 2@ Using Solid-Metal-Mediated Epitaxy, *T. LaFave Jr.*, *N. Lakshminarayana*, *A. Faik*, *M.-A. Hasan*, University of North Carolina

Buried lateral epitaxial overgrowth of Si on thin SiO@sub 2@ layers (<100 nm) using a thick solid Al layer as growth mediator was demonstrated using a newly developed solid-metal-mediated molecular beam epitaxy (SMM-MBE) method. The experiments were carried out at growth temperatures T@sub s@ < 500 °C using electron beam evaporation for Si and thermal evaporation of Al from an effusion cell. Si(100) wafers were thermally oxidized and patterned to provide seed/oxide strips ranging from 2/2 to 50/500 microns. Each seed/oxide strip was repeated within an area of ~ 1.25x2.00 cm@super 2@ and all patterns were placed on the same wafer. The wafers were then thermally etched at T@sub s@ = 900 °C under UHV conditions to desorb the remnant native oxide from the seed areas followed by deposition of Al at room temperature. Si deposited on the resulting structure at T@sub s@ < 500 °C re-grew epitaxially at the buried Al/Si interface and growth was extended laterally over the oxide layer. Initial TEM results demonstrated lateral growth of single crystalline Si over the oxide laver. This SOI method described above is based on SMM-MBE. In SMM-MBE, silicon grows epitaxially at a buried Al/Si interface during thermal evaporation of Si. Si atoms diffuse through the Al overlayer to the interface where low-energy atomic Si sites act as sinks for the diffusing Si atoms. This process is fundamentally different from surfactant assisted growth in which a small concentration of a metal (typically a fraction of a monolayer) is used to enhance epitaxial growth. In SMM-MBE, the Al layer can be thousands of monolayers thick (solid). The new findings may lead to new silicon-on-oxide fabrication method. Also, it provides a procedure for combined metallization and heavy p-type doping, e.g. in MOS device structure. Applications of this method in device fabrication will be discussed.

SC+EL+SS-WeP25 Field-Assisted Metal-Induced Crystallization of Amorphous Silicon Films, A. Khakifirooz, S.S. Mohajerzadeh, S. Haji, University of Tehran, Iran

Recently, metal-induced crystallization has gained special attention for lowtemperature fabrication of polysilicon thin-film transistors. Metal-induced lateral crystallization, has been successfully utilized for obtaining highperformance TFTs. Very large silicon grains, free of metal contamination, are formed as a result of this lateral growth, providing a high carrier mobility. However, the lateral growth rate is still low and very long time annealing is required for practical applications. It has been reported that applying an electric field may enhance the growth rate. We have also observed this effect and the obtained results will be reported. Amorphous silicon films with a thickness of 1000Å are deposited on 50µm thick glass substrates via e-beam deposition. A 1000Å thick passivation oxide layer is subsequently deposited with e-beam and windows are opened for metal pads. A 1000Å thick nickel film is then deposited and patterned using photolithography. Samples are annealed on a hot plate while a DC voltage

up to 100 V is applied between the pads. Growth rate is monitored using optical microscopy. SEM, TEM, and XRD are also used to investigate the crystalline structure of the films. A 300 μ m crystallization was observed in samples annealed at 400°C for 30 min. when a 100 V/cm field applied. This is much higher than the previously reported growth rates. This may be explained by the fact that we have applied the field directly to metal pads, allowing a considerable current to pass through the a-Si film. Three regions with different crystalline structure are clearly observed in the laterally crystallized area when a high voltage is applied. The mechanism behind these phenomena will be discussed. In addition to filed-enhanced diffusion of Ni atoms, which has been supposed to be responsible for enhanced growth rate, we study the role of energetic electrons. Effect of impurities on the growth kinetics will be also reported.

SC+EL+SS-WeP26 Medium Range Order in Amorphous Silicon Films as a Function of Low-Energy Particle Bombardment During Growth, *J.E. Gerbi*, *J.R. Abelson*, University of Illinois at Urbana-Champaign; *P.M. Voyles*, University of Illinois and NEC Research Institute; *M.M.J. Treacy*, NEC Research Institute; *J.M. Gibson*, Argonne National Laboratory

Medium range order (MRO) refers to atomic correlations on a length scale of 1-2 nm. The recently developed TEM fluctuation microscopy technique@footnote 1@ is directly sensitive to MRO, as opposed to diffraction-based methods which are notably insensitive. In this work, we quantitatively compare the MRO in nominally amorphous hydrogenated Si thin films grown by significantly different vapor phase methods: plasma enhanced CVD, hot-wire (HW) CVD, and reactive magnetron sputtering (RMS). All films show significant MRO in the as-deposited state; the MRO decreases upon light soaking or thermal annealing, indicating the existence of a metastable state in the starting material. We investigate the roles of various particle bombardments in producing MRO with the RMS and HW-CVD growth processes. In previous work, we showed that bombardment by ions or neutrals promotes the formation of nanocrystalline or polycrystalline Si, depending on hydrogen addition and substrate temperature. We compare the MRO of a-Si:H, a-Si:D, and a-Si grown by RMS under high argon ion flux with that of a-Si:H grown by HW-CVD, which involves essentially no particle bombardment. We discuss how these bombardments affect the "structure" of a-Si in terms of MRO, and explain how this structure evolves during growth using the model of a frustrated polycrystalline growth surface which yields a highly strained, fine-grained "paracrystalline" structure. Such a structure looks amorphous in conventional diffraction methods, but is topologically crystalline. By contrast, the model of a continuous random network structure, as usually assumed for amorphous films, does not fit the data for as-deposited material. @FootnoteText@ @footnote 1@ J.M. Gibson, et al. Appl. Phys. Letts. 73 3093 (1998).

SC+EL+SS-WeP27 Cluster Deposition Study by Molecular Dynamics Simulation: Al Cluster and Cu Cluster, J.-W. Kang, K.-S. Choi, E.-S. Kang, K.-R. Byun, H.-J. Hwang, Chung-Ang University, Korea

Ionized cluster beam deposition for semiconductor interconnection technology has attracted much attention as a promising method for growing high-quality films at low substrate temperature. Therefore, it is important to understand the interaction between energetic cluster and substrate. In this work, we investigated energetic copper and aluminum clusters deposition and cluster-surface interactions. In the work, we used copper and aluminum clusters with the face centered cubic structure, a classical molecular dynamics simulation, and the second-moment approximation of tight-binding scheme. We simulated cluster deposition and investigated the variations of substrate temperature and the number of disordered atom as a functions of time, energy, and cluster size. The maximum substrate temperatures after energetic cluster impact on surface had linear relationship with total cluster energy and energy per atom, but we could not find any specific relationship with time taken for substrate temperature to reach its maximum. In this work, the correlated collisions between atoms in the cluster played a very important role in the impact on substrate surface and the correlated collision effect was proportional to the cluster size and kinetic energy per atom. For each impact angle and energy, we calculated the average properties such as sputter yield, sticking probability, average reflection angle of the impact cluster, and average emission angle of the sputter products. The calculated properties were compared with that of single atom deposition.

Dielectrics

Room 312 - Session DI+EL+MS-WeA

Alternate Gate Dielectrics

Moderator: R. Ramesh, University of Maryland

2:00pm DI+EL+MS-WeA1 Materials Considerations for High-K Gate Dielectrics for Scaled CMOS, G.D. Wilk, Lucent Technologies; R.M. Wallace, University of North Texas INVITED

Many materials systems are currently under consideration as potential replacements for SiO@sub 2@ as the gate dielectric material for sub-0.13 μ m CMOS technology. A systematic consideration of the required properties of gate dielectrics, however, indicates that the key issues for selecting a high-k dielectric are permittivity and band offset, thermodynamic stability, crystal structure, and compatibility with the current or expected materials to be used in processing for CMOS devices. Many dielectrics satisfy some of these criteria, but very few materials actually satisfy all. A review of current work and literature in the area of high-k gate dielectrics is given, and some conclusions are drawn for various systems based on reported results and fundamental materials considerations.

2:40pm DI+EL+MS-WeA3 New High k Thin Films with Improved Physical and Electrical Properties, Y. Kuo, J. Donnelly, J. Tewg, Texas A&M University

When the minimum device dimension is shrunk to 100 nm, the conventional silicon oxide cannot fulfill many requirements of the device.@footnote 1@ For example, the thin gate dielectric layer (e.g., < 1.2 nm) will have a high leakage current and cannot stop the boron penetration. The dielectric constant of silicon oxide (e.g., 4.0) is too low for the small-size storage capacitor cell. Therefore, it is urgent to develop a new kind of thin film dielectric that has a high dielectric constant (high k) and can satisfy all stringent material, process, and device requirements. Metal oxides are ideal candidates for the gate dielectric application because their compositions are simple and their k values are high enough to last for next several generations of devices. In addition to the high interface states, a metal oxide has the problem of high leakage current, which is caused by the polycrystalline phase formation during the high temperature process.@footnote 2,3@ In this paper, we present new results on high k metal oxides that have high amorphous-to-polycrystalline transition temperatures. By adding a third element into tantalum oxide, e.g., Ti, Cu, and Mo, the film can exist in the amorphous phase in an extended temperature range. The leakage current at a high temperature is lowered. Material and electrical characteristics of the new film, e.g., by xray diffraction, ellipsometer, current-voltage and capacity-voltage curves, will be shown and discussed. The influence of the deposition process, i.e., reactive co-sputtering, to film properties will also be presented. These new high k dielectrics have the potential of being used as gate dielectrics in future MOS devices. @FootnoteText@ @footnote 1@ International Technology Roadmap for Semiconductors, 1999 ed., SIA, etc. @footnote 2@ S. R. Jeon, S. W. Han, and J. W. Park, J. Appl. Phys. 77, 5978, 1995. @footnote 3@ R. B. van Dover, R. M. Fleming, L. F. Schneemeyer, G. B. Alers, and D. J. Werder, IEDM, 823, 1998.

3:00pm DI+EL+MS-WeA4 Chemical and Microstructural Separation of Homogeneous Plasma Deposited (ZrO@sub2@)@subx@(SiO@sub2@)@sub(1-x)@ films (x @<=@ 0.5) into SiO@sub2@ and ZrO@sub2@ Phases after Rapid Thermal Annealing in Ar at 900°C, B. Rayner, R. Therrien, G. Lucovsky, North Carolina State University

Zr-silicate alloys along the pseudo-binary join from SiO@sub2@ to ZrO@sub2@ have attracted interest as high-k dielectrics for Si CMOS devices with equivalent oxide thickness extending to 0.6 nm. In this study alloy films were deposited on HF-last and pre-oxidized and/or nitridized Si(100) by remote plasma enhanced chemical vapor deposition using Zr(IV)-t-butoxide. Film and interface chemical composition, local atomic bonding, and film morphology were studied by Auger electron spectroscopy, Fourier transform infrared absorption, X-ray diffraction, and Rutherford back-scattering. These studies identified two alloy regimes: (i) SiO@sub2@-rich compositions to the compound silicate, ZrSiO@sub4@ (x = 0.5), where properties may be suitable for high-k applications, e.g., films are amorphous on deposition and remain so up to at least 800°C, and (ii) ZrO@sub2@-rich composition, or after relatively low temperature (< 600°C)

anneals. Alloys in the SiO@sub2@-rich regime are chemically-ordered asdeposited at ~350°C with predominantly Si-O-Si and Zr-O-Si bonds, but after annealing in Ar at 900°C for 60 s, separate chemically and microstructurally into SiO@sub2@ and ZrO@sub2@ phases. The ZrO@sub2@ phase is crystalline at the ZrSiO@sub4@ composition. This separation may limit integration of these films into devices which incorporate polycrystlline-Si gate electrodes requiring dopant activation at temperatures > 900°C. Capacitance-voltage and current-voltage characteristics will be presented for as-deposited and annealed films to illustrate the effects of chemical phase separation and crystallization in defining maximum post deposition processing temperatures.

3:20pm DI+EL+MS-WeA5 A Study of ZrO@sub2@ and Zr-silicate Thin Film for Gate Oxide Applications, S.-W. Nam, Yonsei University & Samsung Electronics Co., Korea; J.-H. Yoo, H.-Y. Kim, D.-H. Ko, Yonsei University, Korea; S.-H. Oh, C.-G. Park, Pohang University of Science and Technology (POSTECH), Korea; H.-J. Lee, Stanford University

We investigated the microstructures and electrical properties of ZrO@sub2@ and Zr-silicate thin films deposited by reactive DC magnetron sputtering on Si substrate for gate dielectric application. The films deposited on Si with various deposition conditions and annealing treatments were analyzed by spectroscopic elipsometry, XRD, AFM and XPS. The refractive index of the ZrO@sub2@ thin films increased upon annealing. The ZrO@sub2@ film deposited at low temperature and low power showed amorphous structure, which the films deposited at high temperature and high power showed crystalline structures. The growth of the interfacial oxide between ZrO@sub2@(or Zr-silicate) and Si substrate was observed by cross sectional HR-TEM. C-V and I-V measurements of the MOSCAP structures showed that the accumulation capacitance value and the leakage current level decreased upon annealing in O@sub2@ gas ambient, which is explained by the formation of the interfacial SiO@sub2@ layer.

3:40pm DI+EL+MS-WeA6 Ultra-thin Zirconium Oxide Films Deposited by Rapid Thermal CVD for MOSFET Applications, Y. Lin, J.P. Chang, University of California, Los Angeles

The increasingly tighter process specifications for the next generation microelectronic devices dictate the usage of metal oxides such as zirconium oxide as insulators for better process control and a more reliable dielectric/silicon interface.@footnote 1@ Zirconium t-butoxide is used with O@sub 2@ in this work to deposit zirconium oxide in a RTCVD system. The deposition temperature can be rapidly ramped to and controlled at 400-600°C, and the physical properties of the ZrO@sub 2@ films are characterized by XPS, XRD, AFM, TEM, and spectroscopic ellipsometry to determine the film compositions, chemical states, film microstructures, morphology, thickness, and index of refraction. Amorphous and nearly stoichiometric ZrO@sub 2@ has been deposited with less than 0.2nm variation in thickness across a 4" wafer. The dielectric constant is 3-4 times greater than that of SiO@sub 2@. Leakage current of a ZrO@sub 2@ film with an effective oxide thickness of 10 Å is three orders of magnitude lower than that of a 10Å thermal SiO@sub 2@ film. Post-deposition annealing at 500-700°C is shown to be effective in removing the majority of the incorporated carbon and further reduce the leakage current. However, there exists an optimal carbon doping level where carbon effectively passivates the electrically active defects and reduces the leakage current. We propose a simple kinetic model to describe the heterogeneous reactions responsible for the film deposition. NMOS transistors are fabricated and tested to determine the dielectric constant, leakage current, I-V and C-V characteristics of the zirconium oxide films. Moreover, stress induced leakage current and time dependent dielectric breakdown will also be detailed to assess the material reliability for its applications in microelectronics. @FootnoteText@ @footnote 1@G. D. Wilk, and R. M. Wallace, "Electrical properties of hafnium silicate gate dielectrics deposited directly on silicon," Appl. Phys. Lett., 74(19), 2854(1999).

4:00pm DI+EL+MS-WeA7 High-quality Ultrathin Fluorinated Silicon Nitride Gate Dielectric Films Prepared by Plasma Enhanced Chemical Vapor Deposition Employing NH@sub 3@ and SiF@sub 4@, H. Ohta, M. Hori, T. Goto, Nagoya University, Japan

The silicon nitride (SiN@sub x@) film attracts much attention as scaled gate dielectric films in next generation@super ,@s ULSI. However, the conventional SiN@sub x@ film has a poor interface with silicon and is leaky due to a high trap density in the film. Recently, we have developed ultrathin fluorinated SiN@sub x@ films formed by ECR-PECVD employing NH@sub 3@/SiF@sub 4@. It is known that the average bond energy (5.73eV) of Si-F is higher than that of Si-H (3.18eV). Therefore, it is

expected that the Si-F bond in the film should have improved the quality of gate dielectric film. In this study, we have investigated properties of ultrathin SiN@sub x@ films (4nm) formed at 350°C. These films (fluorinated SiN@sub x@ films) contain fewer hydrogen atoms than the conventional SiN@sub x@ films formed by ECR-PECVD employing NH@sub 3@/SiH@sub 4@. As-deposited fluorinated SiN@sub x@ films indicated the excellent hysteresis loop (20mV) in the C-V curve, and reduced the leakage current by several orders of magnitude than the thermal SiO@sub 2@ in the identical equivalent oxide thickness (EOT). These film properties and the surface reactions for the SiN@sub x@ film formation with good guality are discussed on the basis of results of the in-situ XPS, in-situ FT-IR RAS, FT-IR, and thermal desorption mass spectroscopy (TDS). As a result, the control of fluorine concentration in the SiN@sub x@ films was found to be a key factor for forming the fluorinated SiN@sub x@ films with high quality at low temperatures. The fluorinated SiN@sub x@ is very effective for ultrathin gate dielectric films in next generation@super,@s ULSI.

4:20pm DI+EL+MS-WeA8 Elimination of Carbon Impurities in the Metalorganic Chemical Vapor Deposition (MOCVD) of Titanium Dioxide on Silicon, M. Yoon, A.C. Tuan, V.K. Medvedev, University of Washington; J.W. Rogers, Jr., Pacific Northwest National Laboratory

A novel process has been developed for the deposition of titanium dioxide thin films on p-type Si(100) with high quality interfacial characteristics and the absence of carbon. Elimination of carbon contaminants in the titanium dioxide film and at the interface between the oxide and silicon is important because the presence of impurities can severely degrade the electrical properties of the device. This novel process consists of three stages of deposition in an ultra-high vacuum chamber. Initially, a continuous titanium layer is deposited on silicon using a titanium sublimator. This titanium layer is then oxidized using a gas phase oxygen source to form a TiO@sub x@ buffer layer. Subsequently, a titanium dioxide thin film is deposited by MOCVD using titanium tetrakis-isopropoxide (TTIP) at low temperature (below 650K). Auger electron spectroscopy (AES) analysis at each stage of growth shows no evidence of carbon contamination either within the titanium dioxide layer or at the TiO@sub 2@/Si interface. Additional AES measurements suggest that the titanium layer grows on silicon according to the Stranski-Krastanov mode, which permits uniform growth. A carbon-free titanium dioxide thin film was successfully deposited on silicon using this novel process.

4:40pm DI+EL+MS-WeA9 Microscopic Understanding of the Interface for the Heteroepitaxy of Crystalline Oxides on Silicon, S. Gan, D.E. McCready, D.J. Gaspar, Y. Liang, Pacific Northwest National Laboratory

With SiO@sub 2@ approaching its fundamental limit as the gate dielectric in the existing Si-based CMOS technology, searching for alternative gate oxides with high dielectric constants is crucial for the next generation of devices. Recent work showed crystalline oxides such as SrTiO@sub 3@ (STO) is promising as an alternative to SiO@sub 2@ in MOS capacitors. One of the most important issues is how to integrate it into the existing Si-based technology, the first step of which is the growth of epitaxial oxides on Si substrates. Here we present our recent results on the study of the oxidesilicon interface, which plays a critical role in growing high-quality STO films. Employing scanning tunneling microscopy (STM), x-ray photoelectron spectroscopy (XPS), low-energy electron diffraction (LEED), we characterized the interfacial structure of each template layer (Sr and SrO) grown on Si in situ. The results revealed that the strontium covered silicon surfaces exhibit a series of reconstructions, including a (2x1) structure that provides the most stable interface for the growth of oxides. In addition, we used time-of-flight second ion mass spectrometry (TOF-SIMS) and x-ray diffraction (XRD) to investigate the interfacial chemistry and film structure. By combining these techniques, we correlated the interface structures with film properties, which allowed us to identify suitable interfacial templates for optimized growth. @FootnoteText@ Pacific Northwest Laboratory is a multiprogram national laboratory operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

5:00pm DI+EL+MS-WeA10 Formation of Ultrathin Yttrium Silicate by Thermal Oxidation of Yttrium on Silicon, *M.J. Kelly*, *J.J. Chambers*, *D. Niu*, *G.N. Parsons*, North Carolina State University

We show that direct thermal oxidation can be used to form thin (<50@Ao@) high-k metal silicate layers directly on crystalline silicon. Bulk thermodynamics indicates that several high-k metal oxides (including oxides of Hf, Zr, Al, Y, La, etc.) will be stable with respect to silicon dioxide formation when the oxide is in contact with silicon. However, most low temperature approaches (PVD, CVD, or MBE) for metal oxide deposition on silicon involve elementary reaction steps that include metal-silicon bond

formation before oxidation, resulting in uncontrolled interface layers between the metal oxide and silicon. We can utilize this mechanism to form yttrium silicate films on silicon by first sputtering thin (<10@Ao@) metal films on silicon, vacuum annealing at 300-600°C to form a silicide, then oxidizing at 600-900°C. XPS, medium energy ion scattering, and IR indicate film composition is close to yttrium orthosilicate (Y2O3·SiO2) with some excess Y2O3, depending on anneal conditions. Oxidation kinetics (determined from thicknesses measured by TEM) indicate an initial fast oxidation rate (due to oxidation of metal silicide), followed by a slower process (due to oxidation of underlying silicon). CV analysis of 42@Ao@ films show oxide equivalent thickness ~12@Ao@, consistent with dielectric constant ~14. Leakage is <1A/cm2 at 1V in accumulation. IR and XPS indicate that films do not phase separate when annealed up to 900°C for 20 minutes. Thin (<10@Ao@) silicon oxide and nitride interface layers have been formed in-situ by remote plasma exposure before metal deposition and their effect on interface reaction kinetics have been analyzed by XPS and MEIS. Interfacial oxide is observed to have a negligible effect on interface reactions, but results suggest interface nitrogen tends to block silicide formation before oxidation. These results give important insight into controlling interface structure for implementing high-k materials into silicon devices.

Magnetic Interfaces and Nanostructures Room 206 - Session MI+EL-WeA

Magnetic Semiconductors and Hybrid Structures II

Moderator: P.N. First, Georgia Institute of Technology

2:00pm MI+EL-WeA1 Spin-dependent Behavior in Magnetic / Semiconductor Heterostructures, B.T. Jonker, Naval Research Laboratory INVITED

Magnetic / semiconductor heterostructures offer many exciting opportunities for spintronic applications, ranging from hybrid device structures to direct spin injection. We describe here recent results of each. We have fabricated hybrid logic cells which provide fully reprogrammable, nonvolatile logic operation by combining GMR elements with InAs/AISb/GaSb resonant interband tunneling diodes (RITDs). Such programmable cells allow the use of a low component count common building block for multiple logic functions, and combine the low power, high speed operation of the RITD with the nonvolatile character of GMR elements. Electrical spin injection and transport in semiconductors is another promising avenue to add spin-dependent functionality to the many attractive device properties of semiconductor compounds -- it provides a very simple means of spin injection, and significantly broadens the potential for practical applications.@footnote 1-3@ We have recently demonstrated highly efficient electrical injection of spin-polarized electrons into a AlGaAs/GaAs-based quantum well LED heterostructure using a nonlattice matched epilayer of the semimagnetic semiconductor ZnMnSe as the spin injecting contact. The electroluminescence (EL) from the quantum well is strongly polarized, and provides a quantitative measure of spin injection across the ZnMnSe/AlGaAs interface. Other components of the EL spectrum exhibit little polarization, and provide insight into spin relaxation mechanisms. Ferromagnetic semiconductors provide an ideal contact for electrical spin injection and/or transport -- they are closely matched in conductivity and band structure, and require no large magnetic bias field to produce spin polarized carriers. Several candidate materials will be discussed. ** Supported by ONR and the DARPA SPINS program.@FootnoteText@ @footnote 1@ B.T. Jonker et al, submitted. @footnote 2@ R. Fiederling et al, Nature 402, 787 (1999) @footnote 3@ Y. Ohno et al, ibid p. 790.

2:40pm MI+EL-WeA3 MBE Growth of Ni@sub 2@MnIn/InAs (001) Heterostructure, J.Q. Xie¹, J.W. Dong, L.C. Chen, J. Lu, C.J. Palmstrom, University of Minnesota

InAs is the semiconductor of choice for spintronic applications due to the ease of forming ohmic contacts and its high electron mobility. The former arises from the fact that the Fermi level tends to be pinned in the conduction band at the metal/InAs interface. Although no elemental ferromagnetic metals are lattice matched to InAs, Ni@sub 2@MnIn is nearly lattice matched. In the bulk, stoichiometric Ni@sub 2@MnIn is ferromagnetic at room temperature and has the cubic L2@sub 1@ Heusler structure with a lattice parameter 0.2% larger than that of InAs. In this talk, we report on the growth of ferromagnetic Ni@sub 2@MnIn films on (001)

¹ Falicov Student Award Finalist

30

InAs by molecular beam epitaxy (MBE). Both in situ reflection high energy electron diffraction and ex situ X-ray diffraction measurements indicate that Ni@sub 2@Mnln films grow epitaxially on MBE-grown (001) InAs substrates. Vibrating sample magnetometer and superconducting quantum interference device magnetometer measurements show that the deposited films are ferromagnetic with a Curie temperature ~300 K. Our initial results indicate that Ni@sub 2@Mnln grows in a hexagonal Ni@sub 2@In@sub 3@-type structure, which probably results from either interfacial chemistry or composition. In this talk, the effects of interfacial layers on the growth, structure and magnetic properties of Ni@sub 2@Mnln thin films will be discussed.

3:00pm MI+EL-WeA4 Investigation of the Microstructural Dependence of Magnetic Properties for MnSb/Bi Multilayers Grown on Sapphire, *M.L. Reed*, *H.H. Stadelmaier*, *N.A. El-Masry*, North Carolina State University

The microstructural dependence of the magnetic properties for MnSb/Bi multilayer films grown on sapphire substrates by pulsed laser deposition were investigated by X-ray diffraction(XRD), vibrating sample magnetometer (VSM), and magnetoresistance measurements. Typical hysteresis loops for the MnSb/Bi multilayers are characteristic of ferromagnetic materials. However, altering the growth parameters produces a second coercive field indicating the formation of a second magnetic phase. XRD analysis identified the presence of a peak centered between (0002)MnSb and (0002) MnSb, which in previous samples had not been observed. A change in the relative planar Hall resistance from 1% to 16% with applied magnetic field was also observed in the films that exhibit this second phase. We discuss the nature of this phase and its effect on the magnetic properties of MnSb/Bi.

3:20pm MI+EL-WeA5 Ferromagnetic Fe/Ag-GaAs Waveguide Structures for Wideband Microwave Notch Filter Devices, *W. Wu*, University of California, Irvine; *C.S. Tsai*, University of California, Irvine and Academia Sinica, Taiwan; *C.C. Lee, H.J. Yoo, J. Su*, University of California, Irvine

Ferromagnetic Fe/Ag thin films were epitaxially grown on GaAs substrate by molecule beam epitaxy (MBE) system. Magneto-optic kerr effect (MOKE) experiment was used to measure the magnetization and sample magnetic anisotropy. Ferromagnetic resonance (FMR) peak-to-peak linewidths @delta@H@sub pp@ are identified with the narrowest linewidth of 23 Oe. Wideband electronically tunable microwave band-stop filters were successfully fabricated utilizing both the flip-chip and the integrated configurations, using Fe/Ag-GaAs waveguide structures. The coupling between the microwave signal and the spin excitations happened in ferromagnetic Fe films. Maximum coupling and thus strong attenuation of the microwave power occur at the FMR frequency of Fe, as determined by the applied magnetic fields. A frequency tuning range of 10.6 to 27.0 GHz has been measured with the flip-chip type filter. For the integrated type filter, a tuning range as large as 10.7 to 36 GHz for the peak absorption carrier frequency of a propagating microwave has been accomplished by varying a magnetic field from 0 to 4,600 Oe. Our studies show that Fe/Ag-GaAs waveguide structure is a very promising system for use in future microwave magnetoelectronics as they have well-defined magnetic properties, as well as favorable electrical properties.

3:40pm MI+EL-WeA6 Non-Volatile Reprogrammable Logic Elements using a Hybrid RTD-GMR Circuit@footnote 1@, A.T. Hanbicki, R. Magno, S.-F. Cheng, Naval Research Laboratory; J.E. Mattson, Naval Research Laboratory, US; Y.D. Park, A.S. Bracker, B.R. Bennett, B.T. Jonker, Naval Research Laboratory

Programmable logic devices and gate arrays are increasingly important in new computation and digital logic systems. The resonant tunneling diode (RTD) is an especially attractive device component for such applications because it offers high frequency and low power operation due to its unique IV characteristics. It has been shown that memory, multi-value logic and monostable-bistable logic elements (MOBILE)@footnote 2@ can be constructed using RTDs and FETs. We describe here the fabrication and operation of programmable gates and logic cells based on the combination of RTDs with magnetic elements, yielding fully reprogrammable, nonvolatile functions. The circuits discussed are constructed with resonant interband tunneling diodes (RITD) combined with giant magneto-resistance (GMR) elements. The RITDs are fabricated from MBE-grown InAs/AISb/GaSb/AISb resonant tunneling structures using standard processing techniques, and provide a peak current of 1.4 x 10@super 4@ A/cm@super 2@. The GMR elements consist of Co/Cu multilayers, and exhibit a value of @DELTA@R/R = 28% at 300 K (CIP). Simple series and parallel circuit combinations demonstrate continuous or 2-state tunability of the RITD I-V characteristic. Threshold detection is demonstrated, for the

RITD and GMR in series, by ramping the magnetic field. With the elements we have chosen, the output can be switched by 0.5 V. MOBILE-like inverter operation is observed in a GMR/2-RITD circuit. Specifics of several other circuits will also be discussed. Work is in progress to fabricate an on-chip GMR/RITD integrated circuit. @FootnoteText@ @footnote 1@This work was supported by the Office of Naval Research. @footnote 2@K. Maezawa and T. Mizutani, Jpn. J. Appl. Phys., 32 (1993) L42.

4:00pm MI+EL-WeA7 Magnetization-Controlled Resonant Tunneling in Magnetic Heterostructures, D.O. Demchenko, A.N. Chantis, A.G. Petukhov, South Dakota School of Mines and Technology

Recent advances in molecular beam epitaxial growth made it possible to fabricate exotic heterostructures comprised of magnetic films or buried layers (ErAs, Ga@sub x@Mn@sub 1-x@As) integrated with conventional semiconductors (GaAs) and to explore quantum transport in these heterostructures.@footnote 1,2@ It is particularly interesting to study spin-dependent resonant tunneling in double-barrier resonant tunneling diodes (RTD) with magnetic elements such as GaAs/AlAs/ErAs/AlAs/GaAs, Ga@sub x@Mn@sub 1-x@As/AlAs/GaAs/AlAs/GaAs, and GaAs/AlAs/Ga@sub x@Mn@sub 1-x@As/AlAs/GaAs. We present the results of our theoretical studies and computer simulations of transmission coefficients and current-voltage characteristics of resonant tunneling diodes based on these double-barrier structures. Interband resonant tunneling of electrons (ErAs-based RTDs) and resonant tunneling of holes (Ga@sub x@Mn@sub 1-x@As-based RTDs) is considered. Our approach is based on 8x8 k.p perturbation theory with exchange splitting and strain effects taken into account. We analyze Zeeman splittings of different resonant channels as a function of magnetization. We found that resonant tunneling I-V characteristics of the double-barrier magnetic heterostructures strongly depend on the doping level in the emitter as well as on the orientation of the magnetization. The peculiarities spinin GaAs/ErAs- and GaAs/GaMnAs-based dependent tunneling heterostructures are explained in terms of strong interaction of confined hole states with magnetization, spin-orbit interaction and angular momentum selection rules. @FootnoteText@ @footnote 1@ D. E. Brehmer, K. Zhang, C. J. Schwartz, S. P. Chau, and S. J. Allen, Appl. Phys. Lett. 67, 1268 (1995). @footnote 2@ H. Ohno, N. Akiba, F. Matsukura, K. Ohtani, A. Shen, and Y. Ohno, Appl. Phys. Lett. 73, 363 (1998).

Semiconductors Room 306 - Session SC+EL+SS-WeA

Semiconductor Alloys

Moderator: P. Desjardins, Ecole Polytechnique de Montreal

2:00pm SC+EL+SS-WeA1 Si-Ge Heterostructures, K.L. Wang, University of California, Los Angeles INVITED

PLEASE SEND US AN ABSTRACT. Thank you.

2:40pm SC+EL+SS-WeA3 Critical Behavior of Epitaxial Si@sub 1x@Ge@sub x@/Si(001) Islands, *R.A. Budiman*, *H.E. Ruda*, *D.D. Perovic*, *B. Bahierathan*, University of Toronto, Canada

We study the island size distributions of three-dimensional Si@sub 1x@Ge@sub x@/Si(001) islands of varying Ge fractions (x = 0.4-0.7) and thicknesses grown by ultrahigh vacuum chemical vapor deposition. The size distributions of the percolating islands obey the dynamic scaling hypothesis due to random percolation process, only in the small island limit. Morphologies of the islands strongly suggest a presence of Smoluchowski ripening mechanism, in which islands collide and ripen. We therefore combine random percolation and Smoluchowski ripening to analyze the size distributions. To understand the critical behavior of the islands as exhibited by their size distributions, we formulate a mean-field theory of coherently strained island formation by incorporating surface energy and strain relaxation. The resulting phase diagram shows that the island formation in Si@sub 1-x@Ge@sub x@/Si(001) is located near the critical region. Order parameter fluctuations can be estimated by calculating the curvature energy for such a system and we find that the strain fluctuation is indeed relevant to properly describe the island formation in the Si@sub 1-x@Ge@sub x@/Si(001) system.

3:00pm SC+EL+SS-WeA4 Growth of Coherent Three-dimensional Si Islands on Ge(111), A. Raviswaran, C.P. Liu, University of Illinois, Urbana-Champaign; J.M. Gibson, Argonne National Laboratory; D.G. Cahill, University of Illinois, Urbana-Champaign

We study the evolution of three-dimensional islands during Si/Ge(111) epitaxy. The strain due to lattice mismatch (4.2% tensile) and the difference in the surface energies (@gamma@@sub Si@>@gamma@@sub Ge@) contribute to the formation of the three-dimensional Si islands. We grow Si islands on pseudomorphic Si@sub 0.15@Ge@sub 0.85@ buffer layers (deposited on Ge(111) substrates) in the temperature range 500°C -650°C using MBE; the (111) orientation is used because the critical thickness of Si layers on Ge(111) is larger than that on Ge(001). We characterize the morphology and relaxation of the Si islands using ex situ AFM, TEM and SEM. Islanding occurs at 1 BL Si coverage, i.e., without the formation of a wetting layer. We observe high densities (~ 10@super 12@ cm@super -2@) of coherent, circular base islands for growth temperatures 500°C - 600°C and low Si coverage (< 2 BL Si). The density and shape of the islands is insensitive to the growth temperature. Beyond a critical width the islands relax plastically, by the nucleation and glide of misfit dislocations; this critical width is ~ 16 nm at 550°C and ~ 25 nm at 600°C. We observe large, incoherent, irregularly shaped islands at higher temperatures (> 600°C) and coverages (> 4 BL Si). As the islands transform from coherent to incoherent, coarsening occurs which results in an increase in the island width and a reduction in the island density. The high temperature (> 600°C) growths show a secondary maximum in the island density near 4 BL Si coverage.

3:20pm SC+EL+SS-WeA5 Adatom Assisted Stabilization of Ad-dimers on Ge(001), E. Zoethout, H.J.W. Zandvliet, B. Poelsema, University of Twente, The Netherlands

Studies of the early stage of near room temperature growth of silicon on Ge(001) have revealed an inconsistency between experimental@footnote 1@ and theoretical@footnote 2@ work. Experimentally a stable cluster has been labeled to be a trough dimer oriented perpendicular to the substrate dimer bonds (D-dimer). The same type of cluster is found in the early stage of near room temperature homoepitaxial growth on Ge(001). Theoretically such a D-dimer is predicted to be energetically unfavorable. It turns out that the apparent D-dimer is actually comprised of three rather than two atoms. The three-atom cluster of Ge or Si on Ge(001) is shown to differ from a trough dimer orientated along the substrate dimer bonds, from a small epitaxial island and also from a three-atom Si cluster on Si(001). The three-atom cluster of Ge or Si on Ge(001) is composed of an ad-dimer in the D-configuration and an adatom on the neighboring substrate dimer row. @FootnoteText@ @Footnote 1@W. Wulfhekel, B.J. Hattink, H.J.W. Zandvliet, G. Rosenfeld, and B. Poelsema, Phys. Rev. Lett. 79, 2494 (1997). @Footnote 2@S.V. Khare, R.V. Kulkarni, D. Stroud and J.W. Wilkins, Phys. Rev. Lett. 60, 4458 (1999).

3:40pm SC+EL+SS-WeA6 C Incorporation during the Growth Of Ge@sub 1y@C@sub y@/Ge(001) from Hyperthermal Beams, J. D'Arcy-Gall, D. Gall, P. Desjardins, I. Petrov, J.E. Greene, University of Illinois, Urbana

C-containing group-IV semiconductor alloys are of interest due to the potential they offer for both band gap and strain engineering in microelectronics. This investigation focuses on the effects of incident particle energy and film growth temperature T@sub s@ on the distribution of C lattice configurations in Ge@sub 1-y@C@sub y@ epitaxial layers grown on Ge(001) from hyperthermal beams obtained by ultra-high vacuum ion-beam sputtering using Kr@super +@. All Ge@sub 1-y@C@sub y@ (y @<=@ 0.03) layers, grown at T@sub s@ = 245-415 °C, are fullycoherent and free of extended defects as judged by high-resolution x-ray diffraction, reciprocal lattice mapping, and transmission electron microscopy. The strain-state of epitaxial Ge@sub 0.99@C@sub 0.01@ alloys grown at T@sub s@ = 300 °C changes from in-plane tension to compression as the Kr@super +@ energy E@sub Kr@ is increased from 300 to 900 eV. This results from an increasing fraction of C incorporated in Ge-C split interstitial sites as a result of the trapping, by substitutional C, of Ge self-interstitials formed due to irradiation by the increasing fraction of sputtered Ge atoms in the high energy tail of the energy distribution. These results are supported by TRIM simulations which show that the number of displaced lattice atoms per incident hyperthermal Ge increases from 0.10 with E@sub Kr@ = 300 eV to 0.24 at 900 eV, and ab initio calculations of layer strain for different C lattice configurations. All Ge@sub 1-y@C@sub y@ alloys grown at E@sub Kr@ = 900 eV are in a state of in-plane compression, which decreases with increasing T@sub s@. Raman scattering results show that the substitutional C concentration in these layers is negligible. Comparison of experimental results with ab initio

calculations reveals that an increasing fraction of C incorporates as C pairs as T@sub s@ is increased due to the higher C-C encounter probability on the growth surface.

4:00pm SC+EL+SS-WeA7 Growth and Characterization of Metastable Ge@sub1-x@C@subx@ Thin Films on Si(100) Substrate., W. Li, D. Guerin, S.I. Shah, University of Delaware

The Ge-C system is of interest due to the possibility of band gap engineering on Si. For strain free deposition of Ge@sub1-x@C@subx@, a carbon concentration in excess of 10% is required, assuming that the system obeys Vegard's law. The maximum equilibrium solubility of C in Ge, however, is only 10@super8@/cm@super3@. Molecular beam epitaxy and chemical vapor deposition have been used to grow metastable Ge@sub1x@C@subx@ thin films with x up to 2.5%. We have used a bias assisted sputter deposition using Ge and C magnetrons to obtain the epitaxial Ge@sub1-x@C@subx@ films with extended carbon solubility. Without any applied substrate bias and C flux, a Ge epitaxial layer on Si(100) substrate was obtained at 750°C with proper substrate preparation. Based on the results of pure Ge epitaxy, C was systematically added. Without the substrate bias, x-ray diffraction analyses show that the films were polycrystalline. With the application of a substrate bias, we were able to obtain epitaxial Ge@sub1-x@C@subx@ films. The Ge (400) XRD peak shifts to higher 2@theta@ were observed indicating C incorporation in the Ge lattice. Extended x-ray absorption fine structure (EXAFS) analyses confirmed that the C was indeed incorporated on the substitutional sites in the Ge lattice. C concentration was determined from XRD, X-ray photoelectron spectroscopy (XPS) and Rutherford backscattering spectroscopy (RBS). A C concentration of up to 5 at.% was obtained. Depth profiles of samples by XPS show that carbon is uniformly distributed in the film. Experiments are underway to study the effects of bias and thickness on the epitaxial deposition of Ge@sub1-x@C@subx@ with even further extension of the concentration of substitutionally situated C in germanium lattice.

4:20pm SC+EL+SS-WeA8 Electrical and Optical Properties of Silicon : Germanium Alloys prepared by DC Magnetron Sputtering, A. Subrahmanyam, S. Karthikeyan, J. Asbalter, Indian Institute of Technology, Madras, India; P. Amirtharaj, National Institute of Standards and Technology

The Silicon: Germanium (Si:Ge) alloys are being used in various semiconductor devices. As is well known, these alloys offer advantages in band gap engineering, and can integrate well with the existing silicon technology. Several studies have been made on these alloys. In the present paper, we report the electrical and optical properties of Si:Ge alloys prepared by DC Magnetron sputtering technique. A 7.5 cm diameter circular magnetron cathode has been designed and fabricated. The balanced magnetron cathode is operated at low pressures (4.0 x 10@super -3@ mbar). Argon is the sputter gas. The target is prepared by bonding commercially available Silicon wafer to the water cooled copper backing plate. A small portion of the erosion area on the magnetron cathode is covered with pure germanium wafer. The alloys of Si:Ge (undoped) are prepared (at room temperature 25°C) on glass and Si substrates. The growth parameters in the present study are : flow rate of argon (180 - 250 sccm), Magnetron power (80 - 225 watts) and germanium content in the alloy. The thickness and refractive index of the films is measured by ellipsometer in the wavelength range 300 - 700 nm. The thickness of these alloy films is about 150 nm. The alloy films have been found to be amorphous. The germanium content in the alloy films is varied between 15 - 30 atomic % and is estimated by EDAX and RBS analysis. The optical absorption and photo conductivity measurements have been made on these alloys. The optical band gap of these alloys is in the range 1.45 - 1.6 eV. The dark conductivity is in the order 10@super-@ mho cm@super-1@. The deposition rate is observed to be linear with the magnetron power till 120 watts.

4:40pm SC+EL+SS-WeA9 Preparation and Characterization of Highly Lidoped a-Se Alloy Films for Thermal Neutron Detectors, K.C. Mandal, B. Dille, R.D. Rauh, EIC Laboratories, Inc.; A. Burger, Fisk University; R.N. Bhattacharyya, National Renewable Energy Laboratory

This paper describes our recent research in developing highly Li-doped a-Se alloys and thin films for thermal neutron detector applications. The grown Li-doped (35 a/o) a-Se alloy thin films have shown high promise for this application due to the presence of Li in high concentrations, high dark resistivity (2x10@super 14@@ohm@. cm), good charge transport properties (mu-tau@sub e@ = 3.2x10@super -6@ cm@super 2@/V), low cost and relatively easy scale up. Highly Li-doped a-Se alloy has been

synthesized in controlled ambient and used for making large area films up to 4x4 sq. inch. The vacuum evaporated a-Se alloy films have been characterized by X-ray diffraction (XRD), atomic absorption (AA), differential thermal analysis (DTA), Raman spectroscopy and X-ray photoelectron spectroscopy (XPS). The detectors fabricated from these films have demonstrated potential for thermal neutron detection for the first time. Details of various steps involved in detector fabrication and testing of these devices will also be presented.

5:00pm SC+EL+SS-WeA10 Instability in Atomic Step Morphology during the Sublimation of Si(111), Y. Homma, P. Finnie, NTT Basic Research Laboratories, Japan

A morphological instability has been predicted to occur during step-flow crystal growth.@footnote 1@ Recently we experimentally demonstrated transitions between stability and instability@footnote 2@ during epitaxial growth on an ultra-flat Si(111) terrace - a terrace which is atomically flat on a 100 µm scale. In this paper, we show that such instability can also occur during step-flow sublimation at high temperatures. Step motion due to sublimation was tracked with in situ scanning electron microscopy. When the size of a terrace becomes comparable to the adatom diffusion length, a new step is nucleated, forming the edge of a new, monolayer-deep crater at the center of an ultra-flat terrace. As a result of successive expansion and nucleation, steps become distributed in a concentric circular pattern. The spacing between steps can be controlled by varying the annealing temperature. When the spacing is less than about 20 μ m, the innermost step is typically smooth and nearly circular. For larger spacings, the innermost crater is irregularly shaped while it is still relatively small. The crater becomes smoother as it expands. The instability is manifest when the width of the lower terrace is much smaller than that of the upper terrace. Since the adatom flux from a step to a neighboring terrace depends on the terrace width, by reducing the size of the stabilizing terrace the instability can be initiated. The behavior of a subliming surface is thus similar to that of the growing surface. @FootnoteText@ @footnote 1@ G. S. Bales and A. Zangwill, Phys. Rev. B 41 (1990) 5500 @footnote 2@ P. Finnie and Y. Homma, Phys. Rev. Lett. to be published.

Thin Films

Room 203 - Session TF+EL-WeA

In-situ Characterization of Thin Film Growth

Moderator: M.C.M. van de Sanden, Eindhoven University of Technology, The Netherlands

2:00pm **TF+EL-WeA1 Monitoring of Thin Film Metallization by Metastable He Atom Scattering**, *G. Witte*, Lehrstuhl fuer Physikalische Chemie I, Germany; *P. Fouquet*, Physikalische Chemie I, RUB, Germany

Here we introduce metastable helium atom scattering (MHAS) to characterize metallization transitions occuring during the growth of ultrathin alkali metal (AM) films on metal and semiconductor surfaces. This technique combines the high sensitivity of HAS for measuring coverage and geometrical structure of the adlayer and the extreme surface sensitivity of the metastable atom deexcitation rate to detect modifications of the electronic surface structure.@footnote 1@ In case of Na, K and Cs on Cu(100) an onset of metallization was found at coverages of about half a monolayer. On the other hand for GaAs(110) somewhat larger coverages are required to produce metallic AM films, which are found to grow only below room temperature. These results are in good agreement with previous MDS experiments. Further experiments were carried out for alkali earth metal (AEM) films, where a particular attention is drawn to the comparison of Cs and Ba on Cu(100). It is shown that the onset of metallization for both systems is very similar and can be well described by a 2D Herzfeld model. Finally, MHAS can also be applied to characterize the demetallization of ultrathin AM and AEM films upon adsorption of CO or oxygen.@footnote 2@ @FootnoteText@ @footnote 1@ P.Fouquet and G. Witte, Phys. Rev. Lett. 83, 360 (1999). @footnote 2@ P.Fouquet and G. Witte, Surf. Sci. 454-456, 256 (2000).

2:20pm TF+EL-WeA2 Ultraviolet Absorption Spectroscopy of Polytetrafluoroethylene Deposition by Pyrolytic CVD, B.A. Cruden, K.K. Gleason, H.H. Sawin, Massachusetts Institute of Technology

Polytetrafluoroethylene films have been deposited for use low dielectric constant materials in microelectronic chips. Deposition is performed through pyrolysis of hexafluoropropylene oxide (HFPO) to produce CF@sub 2@, which can then polymerize and deposit as a thin film. The variation of CF@sub 2@ concentration as a function of reactor conditions has been

characterized by UV Absorption spectroscopy. CF@sub 2@ concentration is observed to go through a maximum with respect to both pressure and pyrolysis temperature when it is present in large amounts (~10@sup 14@ cm@sup -3@). The kinetics known for HFPO cracking and CF@sub 2@ recombination are not sufficient to describe these dependencies. An additional mechanism of particle formation, by CF@sub 2@ insertion into (CF@sub 2@)@sub n@ oligomers, has been introduced to produce a kinetic model for CF@sub 2@ concentration measurements. Deposition rates are seen to qualitatively track with CF@sub 2@ concentration variations. Attempting to develop a specific relationship between CF@sub 2@ concentration and deposition rate yields a sticking coefficient of ~4x10@sup -5@, which is consistent with what has been measured in a CF@sub 2@ beam experiment. However, this result does not adequately describe deposition profiles, and under some conditions, higher deposition rates than this sticking coefficient allows for have been observed. These results point to two important factors. First, under regimes of high CF@sub 2@ concentration, gas phase polymerization can produce species that contribute significantly to deposition. Second, it is possible that other properties of the deposition can affect the sticking coefficient. The final observation of note is that deposition only becomes detectable when CF@sub 2@ concentration approaches its maximum value. This might imply that (CF@sub 2@)@sub n@ species may be responsible for deposition.

2:40pm TF+EL-WeA3 Near-edge Valence Band Structure of Amorphous Hvdrogenated SiC Thin Films by a Combined use of Auger and Photoemission Processes, M.-H. Lee, F.S. Ohuchi, University of Washington Although x-ray photoelectron spectroscopy (XPS) nominally provides useful information about the valence-band (VB) electron density of state (DOS), the VB leading edges for Si-C alloys are not adequately evaluated due to large difference in the photoionization cross-sections between Si-3p and C-2p. A core-valence-valance (CVV) Auger transition contains information about the local valence electronic structure of the probed atom due to the direct coupling of the core and valence levels in the Auger process. In addition, the Auger matrix elements give clear pictures of top and maximum of p-like local density of states (LDOS) around Si and C in the near-edge VB region. In this talk, a combined use of the Auger and photoemission processes for site-specific information about the local density of states (LDOS) and the leading edge in the VB will be described. Binding energy-corrected Auger line shape for each of Si and C was obtained to identify the valence electronic structure in the particular case of amorphous hydrogenated SiC (a-Si@sub 1-x@C@sub x@:H) thin films fabricated by plasma enhanced chemical vapor deposition. In the C-rich region (x @>=@ 0.6), the leading VB edge was defined by C-2p, while the VB edge was determined by both Si-3p and C-2p in Si-rich region (x < 0.6). The conduction band (CB) edge was assigned by electron energy loss spectroscopy (EELS) with Si-2p electron-associated energy loss. The band gap energies obtained from the VB and CB edges were compared to those from optical absorption measurements.

3:00pm **TF+EL-WeA4 Growth of Oxygen-rich Films on Ru(0001)**, *A. Böttcher*, *B. Krenzer*, *W. Stenzel*, *H. Conrad*, Fritz-Haber-Institut, Germany; *H. Niehus*, Humboldt-Universität, Germany

The potential of photoemission electron microscopy (PEEM) has been utilized for monitoring the modifications of Ru(0001) induced by surface oxidation. The PEEM images of the initial oxidation stages exhibit bright patterns appearing on dark background. The former represent the precursor phases of regular oxides, Ru@sub x@O@sub y@. The background reflect the termination of the Ru(0001) surface by the chemisorbed oxygen layer. The growth of the Ru@sub x@O@sub y@ from nucleation centers to a thick oxide film strongly depends on the oxidation temperature. Three phases differing by characteristic morphologies have been distinguished. For low temperatures, TT@sub H@, the Ru@sub x@O@sub y@ phase manifests itself by very bright discs randomly distributed over large dark areas. For moderate temperatures, T@sub H@>T>T@sub L@, long stripes appear and grow along the main crystallographic directions of Ru(0001). This growth is initiated by formation of light grains. Further oxidation proceeds via a growth of starshaped and linear islands following the hexagonal symmetry of the substrate and leads finally to the formation of an ordered network. The growth modes result from destabilization of the Ru surface.@footnote 1@ The thick oxygen-rich films created under low- and moderate-temperature oxidation regime are thermally unstable. PEEM images become gradually dark when keeping the sample at temperatures higher than the oxidation temperature. This transformation reveals the cluster formation of stoichiometric oxides as well as a rearrangement of Ru and O atoms across

the thick oxygen-rich layer. All mesoscopic-scale structures studied offer adsorption sites for surplus atomic oxygen adsorbed when exposing them to oxygen at room temperature. @FootnoteText@ @footnote 1@A. Böttcher, H. Conrad, H. Niehus, J. Chem. Phys. 112 (2000) 4779.

3:20pm TF+EL-WeA5 In-situ Characterization of Thin Film Growth, W. Fukarek, Research Center Rossendorf, Germany INVITED

Real time ellipsometry provides information on the dielectric function and dynamic film thickness when applied to film growth or etching. Density depth profiles can be derived either from refractive index depth profiles or from dynamic growth rate data if the flux of film forming particles is known and the sticking probabilities and sputter yield remain constant during growth. Absolute density depth profiles are obtained by scaling the integral to the areal mass density as obtained from ion beam analysis. In-plane stress in thin amorphous or nanocrystalline films, where diffraction methods can not or only hardly be applied, can be measured in situ also under harsh conditions employing optical sampling of cantilever bending. From real time film thickness and curvature measurement instantaneous stress depth profiles are derived with a depth resolution in the nanometer range. The synergistic effects on the information obtained from ellipsometry, particle flux, and cantilever bending data recorded simultaneously are demonstrated exemplarily for ion beam assisted deposition of boron nitride films. In turbostratic (tBN) films the density is found to increase slightly with film thickness whereas the compressive stress decreases, indicating an increasing quality and/or size of crystallites in the course of film growth. In the case of growth of cubic (cBN) films the density starts to increase rapidly from the value characteristic of tBN up to the density of cBN (3.6 g/cm@super 3@). Comparison with the dark field TEM graph recorded from the cBN reflex reveals that the increase in density coincides with the nucleation and increase in crystallite size of cBN. The density remains constant when coalescence of the cBN crystallites is observed in dark field TEM. In contrast to the growth of tBN the depth profile of the instantaneous compressive stress in cBN films is found to be very complex and not directly related to changes in crystalline structure.

4:00pm TF+EL-WeA7 Characterization of the Phase Evolution of Boron Nitride Thin Films using Real Time Multichannel Ellipsometry from 1.5 to 6.5 eV, J.A. Zapien, R. Messier, R.W. Collins, The Pennsylvania State University

Cubic boron nitride (cBN) is the second hardest material after diamond. This property together with its superior chemical and thermal stability makes it a very promising candidate for hard coating applications. The layered structure of cBN films on crystalline silicon (c-Si) substrates is well documented. It is commonly accepted that a sequence of amorphous and hexagonal (hBN) layers grow prior to cBN nucleation. This sequence has been described by real time measurements including polarized infrared reflectance (PIRR) spectroscopy, and infrared spectroscopic ellipsometry (IRSE). The demand for real time characterization techniques is motivated by the use of complex deposition sequences used to optimize film characteristics. Recently, we have developed a rotating polarizer multichannel ellipsometer with spectral capabilities that extend well into the uv range. With this instrument, 132 spectral points in the ellipsometric parameters (@psi@, @DELTA@) covering the photon energy range from 1.5 to 6.5 eV can be collected with a minimum acquisition time of 24.5 ms, while maintaining sub-monolayer sensitivity. As a result of the uv-extended capabilities, the new multichannel ellipsometer is well suited to study wide band gap materials in real time during preparation. Here we report the use of the uv-extended multichannel ellipsometer to study the growth and layered structure of cBN films deposited on c-Si using two processes: i) rf magnetron sputtering of a BN target with pulsed dc substrate bias, and ii) pulsed dc sputtering of a B@sub 4@C target with rf substrate bias. The phase evolution of the BN films based on the optical response in the visible-uv spectral region has been found to be in good agreement with exsitu Fourier Transform Infrared Spectroscopy (FTIR) performed at the end of the deposition. The effect of the deposition conditions on the phase evolution and optical properties of the films will be presented.

4:20pm TF+EL-WeA8 Deposition of Hard Amorphous Hydrogenated Carbon Films from Hyperthermal Hydrocarbon Radicals, Studied by In Situ Real Time Infrared Spectroscopy, *A. von Keudell*, Max-Planck-Institut für Plasmaphysik, Germany; *K.Y. Letourneur*, TU Eindhoven, Netherlands; *M.C.M. van de Sanden*, TU Eindhoven, Netherlands, The Netherlands Dense and hard amorphous hydrogenated carbon films are deposited from a cascaded arc discharge from argon and using remote acetylene (C@sub 2@H@sub 2@) injection. The film formation is monitored by means of real time in situ ellipsometry and real time in situ infrared spectroscopy. From an enhanced infrared absorption at 3300 cm@super -1@ at the surface during deposition, corresponding to the stretching mode of sp@super 1@ hybridized CH groups, it is concluded that C@sub 2@H is the dominant growth precursor. This surface enhancement of the concentration of sp@super 1@ hybridized CH groups increases with increasing growth rate and film density. This variation of the growth rate and the variation of the film properties like mass density, hardness and hydrogen content can be well described by the balance between the contribution of C@sub 2@H and C@sub 2@H@sub 2@ to the incorporated carbon flux.

4:40pm TF+EL-WeA9 In-Situ Monitoring of Adsorption and Film Growth Using Infrared Reflection Absorption Spectroscopy, V.M. Bermudez, W.J. DeSisto, Naval Research Laboratory

Chemical methods for thin-film growth and processing, such as CVD, suffer from a lack of techniques for surface-sensitive, chemically-specific diagnostics under steady-state conditions. Infrared reflection absorption spectroscopy (IRRAS) has been demonstrated as a viable approach to addressing this need. Polarization modulation (PM) has been coupled with a Fourier transform IR spectrometer, permitting the use of linear dichroism to distinguish weak, polarized surface absorptions from strong, isotropic gas-phase absorptions. Buried metal layers have been used both to increase the IRRAS sensitivity to adsorbates on nonmetallic surfaces and to impose the high degree of polarization needed for detection of surface species. Numerical modelling, via the Fresnel relations, has also been included as an integral part of the experiment. This approach has been used to observe the different @delta@@sub s@ frequencies of NH@sub 3@ adsorbed on Al nitride, oxide and oxynitride in a 200 Torr NH@sub 3@ ambient, which can be understood in terms of the different Lewis acidities of the surface Al cations. The optical system has been mated with a production CVD facility and used to observe the steady-state growth of Cr@sub 2@O@sub 3@ thin films on Al@sub 2@O@sub 3@ by reaction of Cr(CO)@sub 6@ and O@sub 2@ at @<=@270 °C. The T-dependence of the physisorbed Cr(CO)@sub 6@ coverage measured with PM-IRRAS gives a desorption energy of 11 Kcal/mol, indicating a weak interaction with the substrate. The growth rate of the Cr@sub 2@O@sub 3@ film is first-order in the Cr(CO)@sub 6@ pressure (both quantities having been obtained from IR data). Modeling of the IR data shows interfacial roughness to be important in this system.

5:00pm **TF+EL-WeA10** Investigation of the Subsonic Beam behaviour of an **Expanding Thermal Plasma used to Deposit Silicondioxide like Films**, *M.F.A.M van Hest*, Eindhoven University of Technology, The Netherlands, Eindhoven; *D.C. Schram*, Eindhoven University of Technology, The Netherlands; Netherlands; *M.C.M. van de Sanden*, Eindhoven University of Technology, The Netherlands

Silicondioxide like films are deposited using a remote thermal argon plasma generated by means of a cascaded arc (p=0.1 - 0.2 bar). Into this remote argon plasma, which expands into a vacuum vessel (p=0.1 mbar), two precursors are injected. First Oxygen is injected at the arc nozzle, and downstream HMDSO (hexamethyldisiloxane) is injected by means of an injection ring. By studying the behaviour of the expanding beam for various plasma conditions a better insight is created in the plasma chemistry. The plasma is analysed by means or Langmuir probe and Pitot tube measurements. Furthermore the growth is studied in situ by means of HeNe ellipsometry and infrared reflection absorption spectroscopy. By means of the Pitot tube the expanding gas velocity can be measured at various positions in the plasma reactor, and with this the gas flow pattern in the reactor can be determined. First of all the flow pattern is studied for a pure argon plasma. This is done as function of the carrier gas flow (argon) and arc current, but also for different background pressures. Second the flow pattern is studied when the depositing precursors are added to the expanding argon plasma. The Pitot tube measurements show that in the plasma reactor there is a recirculation flow on the outside of the expansion. The Langmuir probe measurements show the ion density in the plasma beam. From the combination of the Langmuir probe measurements and the Pitot tube measurements a possible dissociation mechanism for the deposition precursors will be derived. These results will be combined with the in situ measurements of the film growth to obtain insight in the film growth mechanism.

Dielectrics

Room 312 - Session DI+EL+MS-ThM

Ultrathin Dielectrics and Interfaces

Moderator: Y.J. Chabal, Bell Laboratories, Lucent Technologies

8:20am DI+EL+MS-ThM1 Oxidation of Clean and H-passivated Silicon by Molecular and Atomic Oxygen, X. Zhang, Rutgers University; Y.J. Chabal, Bell Laboratories, Lucent Technologies; E. Garfunkel, Rutgers University; S.B. Christman, E.E. Chaban, Bell Laboratories, Lucent Technologies

The need for uniform and ultra-thin silicon oxides in microelectronics requires a fundamental understanding of the initial oxidation of both clean and H-passivated (HF-etched) silicon in oxygen. We have undertaken a systematic infrared absorption study of molecular O@sub 2@ and atomic O oxidation of H-passivated flat and vicinal Si(111) and Si(100) surfaces. Using an IR transmission geometry for full access to Si-O stretch (900-1250 cm@super -1@) and Si-H bending (600-850 cm@super -1@) modes, we can directly observe the incorporation of oxygen even after H-desorption under ultra-high vacuum conditions. Furthermore, hydrogen at steps can be spectrally distinguished from H on terraces, thus making it possible to correlate the kinetics of H elimination with oxide formation as a function of surface structure. We find that upon 1 Torr exposure at 300@super o@C, the bonding of step hydrogen is preferentially altered on the H/Si(111) surface, with dihydride steps being the most reactive. Yet, the rate of oxidation does not scale with the step density, indicating that direct oxidation of terraces takes place simultaneously. For the Si(100) surface, we contrast the oxidation of the HF-etched (atomically rough surface) with that of the smooth H-Si(100)-(2x1) surface prepared in HHV and that of the clean Si(100)- (2x1) surface in order to extract the mechanism for molecular O@sub 2@ dissociation.

8:40am DI+EL+MS-ThM2 New Oxidation Process Using Collimated Hyperthermal Ozone Beam, T. Nishiguchi, Y. Morikawa, M. Miyamoto, Meidensha Corporation, Japan; H. Nonaka, A. Kurokawa, S. Ichimura, Electrotechnical Laboratory, Japan

As the electronic devices are scaled down, using more reactive process gas than molecular oxygen is required to fabricate an ultra-thin highly reliable Si dioxide film for the gate oxide in MOSFET. We used ozone as an oxidant gas and achieved the enhanced initial oxidation rate, resulting in lower temperature oxidation process. In our experiments using highly concentrated ozone gas, more than 3nm Si dioxide film was obtained within 30 minutes under the conditions of 873K of Si temperature and 10Pa of ozone pressure, where the oxidation hardly proceeds by molecular oxygen. In the present study, we carried out the laser ablation of solid ozone in order to obtain collimated ozone beam on the purpose of applying ozone beam to new oxidation processes such as local oxidation of patterned Si surface (e.g. oxidation of a bottom part of a trench). We irradiated a KrF pulsed excimer laser light to highly concentrated solidified ozone that was adsorbed on the sapphire plate cooled down to 30-60K by cryocooler in an UHV chamber. We could obtain collimated ozone beam (within 20° spread) whose supply (typically 10@super 16@ molecules per laser pulse), concentration (typically 70%) and translational energy (3eV maximum) were controlled through the laser ablation conditions such as the laser fluence. Not only the local oxidation but also even lower temperature process is expected using this high-translational-energy (hyperthermal) ozone beam. We will demonstrate the initial oxidation profile for the first 1000 laser shots by Auger Electron Spectroscopy and discuss the applicability of this ozone beam to the semiconductor process.

9:00am DI+EL+MS-ThM3 Nondestructive Investigation of the Si/SiO2 Interface by Spectroscopic Ellipsometry, Reflectance Difference Spectroscopy, Second Harmonic Generation, and X-ray Photoelectron Spectroscopy, J.F.T. Wang, J.W. Keister, Y.M. Lee, G. Lucovsky, J.E. Rowe, D.E. Aspnes, North Carolina State University

We report results of a systematic study with various nondestructive techniques of buried interfaces between Si and thin gate oxides thermally grown at 700C and rapid-thermal-annealed at temperatures to 900C. The objectives are to understand the optical properties, the step structure, and the nature of the chemical bonding of the interface and to determine the limits to which the various nondestructive probes, alone and in combination, can provide this information. We examine in particular data obtained as a function of heat treatment and surface orientation (miscuts 2, 4, 8, 10 degrees off (001) toward the nearest (111); (113); (111); and (110)), with emphasis on the vicinal (001) orientations. The RD spectra of

all as-oxidized vicinal (001) samples decrease by nearly a factor of 5 for the 900C RTA, indicating step-density reduction and a net smoothing of the interface. Except for the 2 deg sample, which shows basically no signal, these spectra become essentially identical to the spectra of chemically etched, H-terminated vicinal (001) surfaces. All such spectra have the appearance of RD lineshapes obtained on (113) surfaces, which are nominally dominated by double-height steps. The ellipsometric data differ mainly in overlayer thickness, but interface information can be extracted through least-squares analysis assuming interface spectra of Si in amorphous and +1 and +2 charge states. To assist in this analysis we orthogonalize the fitting parameters to determine which combinations are best determined by the data. The results indicate that the best reference data are those obtained on H-terminated (111) surfaces. The interface XPS spectra become much more consistent after rapid thermal annealing, with the (001) and (111) spectra being dominated by Si in +2 and +1 charge states, respectively, as expected. This provides further evidence of a reduction in roughness with annealing.

9:20am DI+EL+MS-ThM4 Core-level Photoemission of Interface States on SiO@sub 2@/Si: Substrate Orientation Effects, J.E. Rowe, Army Research Office; J.W. Keister, J.F.T. Wang, North Carolina State University; G.J. Jackson, T.E. Madey, Rutgers University; D.E. Aspnes, North Carolina State University

High resolution soft X-ray photoelectron spectroscopy (SXPS) with synchrotron radiation is used to study the interface of mis-cut SiO@sub 2@/Si(100) [i.e. stepped interface] of device quality ultrathin gate oxides. Our studies were performed on thin oxides grown by thermal oxidation in pure O@sub 2@ at a temperature of 600@degree@C and pressure of ~760 Torr. Our data can be well described by five different Si species due to Si in different oxidation states which are usually labeled Si@super 0@, Si@super +1@, Si@super +2@, Si@super +3@, and Si@super +4@. We have studied a number of samples prepared as described above and find that the energies relative to the SiO peak are 0.95 eV, 1.80 eV, 2.50 eV, and 4.00 eV for the Si@super +1@, Si@super +2@, Si@super +3@, and Si@super +4@ peaks respectively. For this study, we define the transition region as the region containing Si in intermediate oxidation states (Si@super +1@, Si@super +2@, Si@super +3@). We find a transitionregion Si suboxide concentration of 1.3 x 10@super 15@ cm@super -2@ assuming an escape depth of ~7 @Ao@ at a photon energy of 200 eV for samples annealed after growth at temperatures of ~900 @degree@C . This transition region is that in excess of the density ~1 monolayer of Si@super +1@ expected for the most abrupt SiO@sub 2@/Si(111) interface in terms of the Si(111) layer density of 7.8 x 10@super 14@ cm@super -2@. The I@sub 1@ interface peak is largest for (111) and decreases substantially for (113), (110), and for stepped (100) substrates. The total interface density appears to be lowest for Si(100) with a modest step density introduced by a 2@degree@ mis-cut. The step-dependent behavior is consistent with that reported using second harmonic generation. The total concentration of suboxide derived from SXPS data is dependent on the uniformity of SiO@sub 2@ films as well as data modeling, i.e., fitting of the data; both will be discussed.

9:40am DI+EL+MS-ThM5 Spectroscopic and Electrical Characterization of the Evolution of Chemical Oxides Into Ultrathin Gate Oxides, J. Eng, Jr., R.L. Opila, J.M. Rosamilia, J. Sapjeta, Y.J. Chabal, B.E. Weir, P. Silverman, T. Boone, R.L. Masaitis, T. Sorsch, M.L. Green, Bell Labs, Lucent Technologies The goal of this study is to understand how the structure of wet chemical oxides change during oxidation, and to determine whether the quality of ultrathin oxides is sensitive to the type of of wet chemical treatments. Four wet chemical treatments were examined: 1. standard RCA, with an SC1 step (ammonium hydroxide and peroxide) followed by an SC2 step (hydrochloric acid and peroxide), 2. modified RCA, with an HF etch between the SC1 and SC2, 3. ozonated water, and 4. HF. X-ray photoelectron spectroscopy (XPS) and infrared spectroscopy (IR) have been used to probe the structure and composition of the wet chemical oxides. IR probes the long range order in the films, while XPS probes the local Si stoichiometry. Both techniques show that the ozone oxide has the highest quality. Despite large differences in the initial quality of the wet chemical oxides, rapid thermal oxidation of the chemical oxides produces oxide films that are spectroscopically similar. Electrical properties of the oxides will correlated with the spectroscopic studies.

10:00am DI+EL+MS-ThM6 Studies on Accurate Determination of the Physical Thickness of nm Gate Oxides and its Correlation with the Electric Thickness, *D.W. Moon, H.K. Kim, H.J. Lee, H.M. Jo*, Korea Research Institute of Standards and Science, Korea; *H.S. Jang, H. Hwang,* Kwangju Institute of Science and Technology, Korea

Accurate Determination of nm gate oxides is critical for the development of nanoelectronic devices as well as for CMOS device scaling beyond 100 nm. In semiconductor industries, the thickness of gate oxides has been measured by ellipsometry. However, the accuracy has been not evaluated especially for gate oxides thinner than 10 nm. Recently, TEM and spectrometric ellipsometry(SE) have been used to measure the physical thickness of nm gate oxides and the electric methods such as I-V an C-V have been modified to include quantum effects. In this work, to estimate the uncertainty and improve the accuracy of the methods used for gate oxides thickness determination, TEM, SE and Medium Energy Ion Scattering Spectroscopy(MEIS) were used to determined the physical thickness of 6 gate oxides from 9 nm thick to 1.5 nm native oxide thick. MEIS can analyze the composition and structure of ultrathin films with atomic layer depth resolution. It was investigated that MEIS can be a reference for gate oxide thickness determination down to 1-2 nm. The difference of the physical thickness determined with TEM, SE and MEIS were discussed and compared with the electric thickness determined by I-V and C-V methods. For the gate oxides studied, the thickness determined by the Si MEIS peak was 1.5 nm thicker than that by the O MEIS peak. The thickness determined by SE and TEM was between the two values, while SE gave ~0.5 nm higher thickness than TEM. However, with the interlayer thickness, TEM thickness approached that of Si MEIS peak thickness. The electric thickness determined with I-V and C-V was close to that of Si MEIS peak thickness within 0.2nm. The thickness by SE is quite sensitive to the refractive index value used for fitting, especially for gate oxides thinner than 5nm. Based on this multi-disciplinary approach, it will be discussed how to provide standards for nm gate oxides approaching the limit of CMOS and how to transfer the standards to SE which is widely used in semiconductor process lines.

10:20am DI+EL+MS-ThM7 Bonding of Nitrogen in Silicon Oxynitride Films, *R.L. Opila*, J. Eng, Jr., Y.J. Chabal, K.T. Queeney, Bell Laboratories, Lucent Technologies; J.P. Chang, University of California, Los Angeles

Silicon oxynitride is a promising candidate to replace silicon dioxide in the next generation of microelectronic devices, but key aspects of the nitrogen chemistry in this material remain unresolved. This talk describes a twofold approach for understanding nitrogen bonding in these materials. The first approach employs surface analytical techniques, including photoelectron spectroscopy, infrared spectroscopy and near edge x-ray absorption fine structure, to study how oynitride precursors, suchas as nitric acid, nitromethane, and ammonia, react with silicon surfaces. The second approach uses the previous analytical techniques, along with electron spin resonance spectroscopy, to compare the nitrogen bonding states in silicon oxynitride and silicon nitride films prepared by thermal growth and ion implantation. Significant differences in the distribution of nitrogen bonding states and point defects are observed and correlated with the method of film preparation.

10:40am DI+EL+MS-ThM8 Photoemission Investigation of Nitrogen Incorporation at the Si/SiO@sub 2@ Interface, J.E. Rowe, Army Research Office; J.W. Keister, North Carolina State University

Monolayer incorporation of nitrogen at the Si/SiO@sub 2@ interface enhances the reliability and electrical characteristics of this nearly perfect interface for ultrathin SiO2 layers.@footnote 1@ In this paper we demonstrate that the Si(100)/SiO@sub 2@ interface is chemically sensitive to the nitrogen concentration. The nitrogen (1s) Soft X-ray Photoemission Spectroscopy (SXPS) peak was measured for varying degrees of N incorporation using the Advanced Light Source synchrotron at LBL National Lab. The broad width of the N(1s) SXPS peak lineshape is consistent with a large degree of final-state, Gaussian phonon broadening, and is comparable to O(1s) line. However, unlike the O(1s) line which is not especially chemically sensitive, the N(1s) line shows a clearly measureable, interface peak shift@footnote 2@ with increasing N incorporation. The average interface peak binding energy is ~0.75 eV greater than that recently reported for thick "bulk" films of Si3N4 with Al-K" XPS. To a lesser degree, the peak shape is seen to change as well. In particular, the peak width minimizes near to the value ~1.0 ML N incorporation, which is also the level at which devices interfaces perform best electrically. @FootnoteText@ @footnote 1@ G. Lucovsky, A. Banerjee, B. Hinds, B. Claflin, K. Koh, H. Yang. J. Vac. Sci Technol. B 15(4) 1074-1079 (1997).

@footnote 2@ J. W. Keister, J. E. Rowe, J. J. Kolodziej, H. Niimi, H.-S. Tao, T. E. Madey, G. Lucovsky. J. Vac. Sci Technol. A 17(4) 1250-1257 (1999).

11:00am DI+EL+MS-ThM9 Investigation of Fluorine in Dry Ultrathin Silicon Oxides, G. Vereecke, E. Röhr, R.J. Carter, T. Conard, H. Dewitte, M.M. Heyns, IMEC, Belgium

As critical dimensions of integrated circuits continue to decrease, insulators with dielectric constants higher than silicon dioxide will be introduced in capacitors and transistors. However an ultrathin (< 1 nm) silicon oxide layer will generally be needed at the interface between Si and high-k layers. In cluster tools integrating surface preparation and dielectric deposition, vapor HF chemistries are envisaged to etch the native oxide prior to oxide growth. This HF etch leaves F on the surface of the Si wafer, which gets incorporated into the growing oxide. In addition, the silicon subsurface has also been proposed as a source of the F found in these oxides. The presence of F may be beneficial or detrimental for the properties of these layers depending on application, F location, and layer thickness. We have evaluated the sources of F in ultrathin oxides grown by UV/O2 at room temperature in an experimental vapor phase cleaning tool. Surface pretreatment was either by in-situ HF/methanol vapor process or by ex-situ wet HF dip followed by a DIW rinse. Evidence was found for F crosscontamination from the tool gaspanel when the HF etch step was performed in-situ. After correcting for this, F atomic concentrations in oxides grown on vapour HF and wet HF treated surfaces were of about 5 % and 2 %, respectively. The former would lower the dielectric constant of the layer if homogeneously distributed. The level of F contributed by the subsurface was estimated with oxides grown on wet HF treated surfaces in a specially built quartz chamber with no F contamination. No F was detected in these oxides, which indicates that the level of subsurface F is lower than previously reported. Ultrathin oxides continued to grow when exposed to air. This raises concern about their stability during the deposition and annealing of high-k layers. XPS results suggest that this is related to the exchange of labile F groups in the films.

11:20am DI+EL+MS-ThM10 Studies on Electrical Properties of Ultrathin Oxides of Silicon Grown by Wet Oxidation at Low Water Vapor Pressure, *V.K. Bhat, K.N. Bhat, A. Subrahmanyam*, Indian Institute of Technology, India

The rapid downscaling of the device dimension has increased the interest in the ultrathin (< 5 nm) oxides of silicon. Ultrathin oxides with thickness uniformity and good electrical properties are required for the silicon submicron devices. In general, the dry oxidation is being followed to grow these ultarthin oxides. Wet oxidation is not considered for the growth of ultrathin oxides of silicon because of the following reasons: i) high growth rate associated with the conventional wet oxidation at 1 atm. water vapor pressure and ii) large density of electron trapping centres present in the wet oxide. In the present study we report the results on the electrical properties of ultrathin oxides of silicon grown by wet oxidation at low (0.04 atm.) water vapor pressure. Ultrathin oxide of silicon is grown at 900°C on n-type single crystal silicon, single side polished. (100) oriented and having 1-10 @ohm@ cm resistivity (procured from M/s Wacker GmbH, Germany). The grown ultrathin oxides are characterized for their electrical properties by fabricating MOS tunnel diodes (aluminum is thermally evaported with a metal mask on to the ultrathin oxide). The capacitance-voltage (C-V), conductance-voltage (G-V) and current-voltage (I-V) charcteristics of the MOS tunnel diodes are studied. The interafce state density (D@sub it@) and the density of the fixed oxide charge (Q@sub f@) are being calculated. The grown ultrathin oxide thickness is estimated from the measured C-V characteristics and are in the range 2.5-5.0 nm. The oxide growth rate is found to be linear. The charge trapping characteristics of the ultrathin oxides are studied by using consatnt current stress (CCS) technique. The decrease in the gate voltage is observed with the stress time. This observation may be attributed to the positive charge trapping in the oxide during the CCS. The charge trapping is found to be oxide thickness dependent and it decreases with the decrase in the oxide thickness.

11:40am DI+EL+MS-ThM11 Properties of SiO@sub 2@ Thin Films Deposited at Low Temperature on SiGe and Si Samples in O@sub 2@/TEOS Helicon Plasmas, A. Goullet, D. Goghero, V. Fernandez, A. Granier, Institut des Matériaux Jean Rouxel, France; F. Meyer, Université de Paris XI, France; G. Turban, Institut des Matériaux Jean Rouxel, France Silicon dioxide thin films are deposited at low pressure (< 5mTorr) and temperature (<200° C) on Si@sub 1-x@Ge@sub x@ epi-layers and silicon substrates in oxygen rich O@sub 2@/TEOS helicon plasmas. The growth of SiO@sub 2@ films and the evolution of the interfacial layer under applied radio frequency bias voltage (0, -100, -200 V) are investigated using a UV-

Visible phase modulated ellipsometer (1.5-5 eV). The structural properties of the films are studied using infrared transmission spectroscopy, wet chemical etching and spectroscopic ellipsometry. Very thin (<10 nm) SiO@sub 2@ films deposited in the same conditions are investigated by Xray photoelectron spectroscopy and spectroscopic ellipsometry to gain better insight of the oxide/semiconductor interface. The ion energy is found to be a significant parameter both for film properties and deposition rate. Use of radio frequency bias is effective in producing high quality SiO@sub 2@ films but an amorphized transition layer is detected in this case as evidenced by ellipsometric data modeling. The increase in the ion energy is also responsible for the presence of an additional oxidation state which appears on the Ge 3d XPS peak. Complementary capacitive C(V) measurements of grown oxides have been performed using metal-oxidesemiconductor samples. An increase in the fixed oxide charge and interface state densities as a function of the applied bias voltage is observed for silicon substrates whereas the electrical properties of the films deposited on Si@sub 1-x@Ge@sub x@ are rather insensitive to the deposition conditions.

Organic Films and Devices Room 313 - Session OF+EL+SS-ThM

Organic Thin Films

8:20am OF+EL+SS-ThM1 Highly Ordered Layers of Large Conjugated @pi@-systems on Cu(111): A Novel Preparation Method, G. Beernink, K. Weiss, A. Birkner, Ruhr-Universität Bochum, Germany; F. Dötz, K. Müllen, Max-Planck-Institut für Polymerforschung, Germany; C. Wöll, Ruhr-Universität Bochum, Germany

With regard to applications in molecular electronics and the fabrication of nanoelectronic devices, polycyclic aromatic hydrocarbons (PAH), e.g. the graphite segment hexa-peri-hexabenzocoronene (HBC), have recently received considerable attention. For such large PAHs, however, the low solubility in organic or polar solvents and the rather large sublimation temperatures make the application of the commonly used deposition methods, namely adsorption from solution or evaporation in a vacuum system (CVD, OMBE) difficult or even impossible. In this work, we present a direct way to synthesize one particular polycyclic aromatic hydrocarbon, namely hexa-peri-hexabenzocoronene (HBC) by using a surface as a template. A modified precursor molecule, 1,2,3,4,5,6-Hexakis(4dodecyloxyphen-1-yl)benzene (HPB), which is not planar, is evaporated on a Cu(111) surface. Heating of the substrate leads via thermally induced cyclodehydrogenation to the product HBC, which is characterized by XPS, X-ray absorption spectroscopy (NEXAFS) and STM. The NEXAFS-data directly demonstrate the formation of flat, graphite-like segments which interact only weakly with the substrate, whereas the STM data reveal a high of lateral order.

8:40am OF+EL+SS-ThM2 The Effect of Conjugation Length on the Frontier Orbital Position of Oligothiophene Derivatives at Metal-organic Interface, *A.J. Makinen, I.G. Hill,* Naval Research Laboratory; *T. Noda, Y. Shirota,* Osaka University, Japan; *Z.H. Kafafi,* Naval Research Laboratory

We report an ultraviolet photoelectron spectroscopy (UPS) study of a novel family of end-substituted oligothiophene derivatives with a varying conjugation length, BMA-nT (n=1-4), where n indicates the number of thiophene rings. These new oligothiophene derivatives are thermally and morphologically stable, and unlike unsubstituted oligothiophenes, which undergo luminescence quenching due to the polycrystalline nature of their solid films, the thiophene derivatives form amorphous films. The BMA-nT compounds show luminescence from the blue (n=1) to the orange (n=4), and additionally they posses hole-transport properties making them attractive materials for organic light-emitting diodes (OLEDs). The UPS results show that the position of the highest occupied molecular orbital (HOMO) of the end-substituted oligothiophenes at the metal-organic interface is dependent on the number of thiophene rings present, i.e. the effective conjugation length of the molecule. We will discuss this property and its implications in the context of carrier injection in an OLED.

9:00am OF+EL+SS-ThM3 Electronic Properties of @pi@-Conjugated Organic Molecular Semiconductor Interfaces, A. Kahn, Princeton University INVITED

Metal/organic interfaces are central to a number of organic-based devices. Their electronic structure and chemistry control charge injection. Modeling these interfaces requires an accurate knowledge of the injection barriers, i.e. the position of the transport levels with respect to the metal Fermi level, and of the role of interface chemical reactions. This talk reviews our latest results obtained via direct and inverse photoemission and scanning tunneling spectroscopy on metal interfaces with five organic materials (PTCDA, CuPc, Alq@sub 3@, @alpha@-NPD, @alpha@-6T) of interest for light emitting device and TFT applications. We present the first accurate picture of the transport levels in these materials, levels which are generally unknown because of the strongly correlated nature of molecular solids. The transport gap is found to be significantly larger, i.e. by the exciton binding energy, than the optical gap usually used to describe interface and bulk molecular level diagrams. The exciton binding energy ranges from 0.4eV to 1.4 eV in the materials investigated. Furthermore, we present a detailed and systematic investigation of molecular level alignment at interfaces of organic thin films deposited on a series of metals with different work function. These demonstrate that one of three mechanisms is involved in the formation of the dipole barriers generally observed at such interfaces: (1) lowering of the metal work function by the molecules; (2) electron transfer from the metal to the organics; (3) chemical bonding. Knowledge of the transport gap, interface level alignment mechanisms and interface chemistry leads to a more accurate description of these organic interfaces. Work supported by the MRSEC program of the National Science Foundation (DMR-9809483).

9:40am OF+EL+SS-ThM5 Effect of Alkyl Substituents on the Adsorption of Thienylenevinylene Oligomers on the Si(100) Surface, *B. Grandidier, J.P. Nys, D. Stievenard, C. Krzeminski, C. Delerue,* IEMN/ISEN, France; *P. Blanchard, J. Roncali,* IMMO Universite d'Angers, France

Conjugated thiophene-based oligomers are subject to intense research activity due among others to their potential use as molecular wires in future molecular electronic devices. As microelectronics technology is based on the use of silicon substrates, there is an increasing need to connect these organic molecules to the existing silicon technology. Due to the low intrinsic solubility of the rigid conjugated chains, the synthesis of the longuest chains required the substitution of alkyl chains to the thiophene ring in order to increase the solubility. Whereas such a substitution has limited effect on the electronic structure of the oligomers, it exerts a strong effect on the interactions of the molecules with their physical and chemical environment. The adsorption of unsubstituted and substituted thienylenevinylene oligomers on the Si(100) surface has been investigated using scanning tunneling microscopy. The mode of substitution of the thiophene ring exerts a strong influence on the adsorption configurations and the images of the oligomer based on 3,4dihexyl thiophene are highly voltage dependent. We discuss the influence of the alkyl chains on the adsorption process and on the appearance of the molecules in the STM images.

10:00am OF+EL+SS-ThM6 Growth of Films of Thiophene Oligomers by Seeded Supersonic Beams to Improve Control on their Quality and Properties, *S. Iannotta*, *T. Toccoli*, *A. Boschetti*, CeFSA - Research Center CNR-ITC for the Physics of Aggregates, Italy; *P. Milani*, INFM - Universit@aa a@ di Milano, Italy; *S. Ronchin*, INFM - Universit@aa a@ di Trento, Italy; *A. Podest@aa a@*, INFM - Universit@aa a@ Bicocca, Italy

The growing interest in pi-conjugated organic molecular materials and polymers, driven by wide potential technological impact in electronics and photonics, still faces severe limitations. Applications would be much more favored by improving control on morphology and structure in the solid state. Standard growth methods are based on the self-assembling of the molecules resulting more or less affected by the interaction with the substrate. Very often the resulting films show an inadequate ordering. These problems become severe as the thickness increases over a few monolayers. Fully considering the major role played by the initial state of the molecules at early stages of growth, we approached the problem combining a supersonic free jets that permit to control kinetic energy, momentum and flux with a UHV deposition apparatus. We perform the deposition and simultaneously control the initial state of the seeded organic molecules by varying the parameters of the supersonic expansion (dilution, temperature of the source, form and diameter of nozzle, etc) [P. Milani and S. Iannotta, Synthesis of Nanophase Materials by Cluster Beam Deposition, Springer, Berlin (1999)]. We have prepared a series of films of alpha quaterthiophene that are then characterized by optical measurement, TM-AFM and X-ray diffraction. We report an overall strong evidence of an unprecedented control on morphology, structure and optical response that correlate well to the beam's parameters. PL spectra at low temperature show the vibronic molecular structure very well resolved depending on the initial state of the oligomer in the beam. Films, several hundreds nm thick, show a high degree of ordering with surface morphologies characterized by layered structures of molecular height. X-

ray diffraction confirms the high degree of ordering induced by the growth from highly supersonic beams. Correlation between morphology, degree of ordering and the optical response of these films will be discussed.

10:20am OF+EL+SS-ThM7 Scanning Tunneling Microscopy/Spectroscopy Investigation of the Organic Molecules PTCDA and HBC on Au(100), *T. Fritz, M. Toerker, H. Proehl, F. Sellam, K. Leo,* TU Dresden, Institut fuer Angewandte Photophysik, Germany

Highly ordered organic thin films on gold single crystals have been investigated by Scanning Tunneling Microscopy (STM) and Scanning Tunneling Spectroscopy (STS) at room temperature. The organic dye molecule perylene-tetracarboxylic-dianhydride (PTCDA) has been deposited as submonolayer coverage on Au(100). I-V-spectroscopy at fixed tip-sample-separations has been performed alternately on the PTCDA islands and on uncovered areas of the Au(100) surface. The corresponding normalized derivatives of these I-V-curves have then been compared to inverse photoelectron spectroscopy data known from literature, indicating resonant tunneling via the lowest unoccupied molecular orbital. As a second molecule peri-hexabenzocorone (HBC), also deposited on Au(100), has been investigated. The Au(100) surface has been fully covered by a few monolayers thick, highly ordered HBC film. The normalized derivatives of I-V-curves measured on these films show a pronounced local maximum at a negative voltage of about -1.4 V. By comparison with ultraviolet photoelectron spectroscopy (UPS) measurements of HBC on Au(111) we can show that this peak in the tunneling spectroscopy plot is due to resonant tunneling via the highest occupied molecular orbital of HBC.

10:40am OF+EL+SS-ThM8 STM, AFM, & Electrochemical Investigations of Squaraine Thin Films, *M.E. Stawasz*, *N. Takeda, B.A. Parkinson*, Colorado State University

Squaraines are a class of organic photoconductors which have found industrial use in photoreceptors of laser printers and xerographic devices, as well as in ablative optical recording material. They have also been investigated for their nonlinear optical characteristics as well as their ability to sensitize large-bandgap semiconductors in photoelectrochemical solar cells. Central to its various uses and characteristics is the squaraine molecules' ability to form organized aggregates, both in solution and in the solid state. Few studies have been done, however, to relate the molecular structure of squaraines to the structure of the aggregates that spontaneously form in thin films. We report STM and AFM data which unambiguously determines thin film/monolayer aggregate structure for a series of hydroxylated and non-hydroxylated dialkylamino-phenyl squaraines with varying alkyl tail lengths deposited on HOPG. Results show that alkyl tail length significantly affects squaraine aggregate structure while the presence or absence of hydroxyl groups does not. Electrochemical investigations of the redox behavior of squaraine thin films using HOPG as the working electrode were also performed. Remarkable redox behavior was observed suggesting a structural change in the squaraine aggregate state upon oxidation. In addition, the effect of electrolyte anion and film thickness on the redox behavior of squaraines was observed, thus providing additional insight into the charge transfer abilities of the squaraine film in the direction normal to the substrate surface.

11:00am OF+EL+SS-ThM9 Work Function Modification and Surface Chemistry of Indium Tin Oxide with Organosilane Self Assembled Monolayers, J.A. Chaney, Naval Research Laboratory; F. Farzad, Geo-Centers, Inc. and Naval Research Laboratory; C.S. Dulcey, R. Shashidar, P.E. Pehrsson, Naval Research Laboratory

Attachment of organosilane SAM's with monomers having different dipole magnitude and direction may permit control of the work function (@PHI@) of indium tin oxide (ITO) substrates used in OLED's. However, reliable measurement of @DELTA@@PHI@ requires reproducible control of the environmental conditions. In this work, ITO substrates were treated with SAM's having different head and attachment groups and then inserted into an ultra high vacuum (UHV) chamber. The SAM/ITO work function was measured using an in-vacuo Kelvin probe calibrated with a graphite standard. Surface chemistry was probed by high resolution electron energy loss spectroscopy (HREELS), and electronic structure was investigated by energy loss spectroscopy (ELS). The SAM-modified surfaces usually had lower work functions (@PHI@ = ~4.8-5.3 eV), than bare, oxygen-plasma treated ITO (@PHI@ = ~5.3 eV). The SAM monomers had either one or three Si-OCH@sub 2@CH@sub 3@ units for attachment to the ITO surface. Trifunctional SAM's gave higher @PHI@ values than monofunctional SAM's. The HREELS of monofunctional SAM/ITO showed structure which may be attributable to bending modes. These modes were more intense

than on the trifunctional counterpart, possibly due to tighter binding of the latter with ITO. Most SAM modified surfaces showed significant deviation in @PHI@ with time and temperature (up to 200°C), suggesting that adsorption of ambient gasses, even in UHV, affects the SAM/ITO system. However, the work function of some SAM's with hydrophobic head groups was apparently unaffected by adsorption. Differences in the band edge transitions of clean ITO vs. SAM/ITO indicate electronic interactions between the SAM and substrate.

11:20am OF+EL+SS-ThM10 Effect of Fluoride Layer Insertion on the Electronic Structures of Al/Organic Interfaces@footnote 1@, Y. Park, Korea Research Institute of Standards and Science, Korea; D. Kim, Hallym University, Korea; S. Cho, O. Kwon, G. Lee, Korea Research Institute of Standards and Science, Korea; E. Cho, Chonnam National University, Korea We have investigated the electronic structures of interfaces between Al and tris-(8-hydroxyquinoline)aluminum (Alq@sub 3@), which is a prototypical organic electroluminescent (EL) material. It has been well known that the insertion of alkali metal fluoride, such as LiF, greatly enhances the EL performance and the origin of such behaviors have been controversial. We used photoelectron spectroscopy techniques including Xray and UV photoelectron spectroscopy (XPS and UPS) as well as resonant photoemission (RPES) to probe the electronic structure change caused by the insertion of thin layer of various alkaline and alkaline earth metal fluorides between Al and Alq@sub 3@. As previously known, the presence of LiF layer enhanced gap-state formation, but even without the LiF layer, Al deposition significantly alters the electronic structures of Alq@sub 3@. While the insertion of CsF layer showed clear enhancement of the gap states, it was much less obvious for CaF@sub 2@ layer. For both materials, the RPES showed very weak resonant enhancement when excited with photons with the energy near Cs and Ca core level absorption edge. We report similar measurements for various other fluoride materials and discuss their implications. @FootnoteText@ @footnote 1@ This work was supported in part by MOST of Korea through National Research Laboratory Program and Atomic-scale Surface Science Research Center.

11:40am OF+EL+SS-ThM11 Interface of Aluminum and Poly(vinylidene fluoride with Trifluoroethylene) Copolymer, B. Xu, C.N. Borca, S. Ducharme, A.V. Sorokin, P.A. Dowben, University of Nebraska, Lincoln; V.M. Fridkin, S.P. Palto, N. Petukhova, S.G. Yudin, Institute of Crystallography, Russia

The interface between aluminum and crystalline copolymer thin films of vinylidene fluoride (70%) with trifluoroethylene (30%) [PVDF-TrFE] has been studied. The ratio of carbon 1s and aluminum 2p core level photoemission peak intensities changes little with increasing emission angle, even after deposition of 5 Å aluminum on the surface of PVDF-TrFE. This indicates that the distribution of aluminum atoms in the copolymer film is quite uniform in the near surface region and that the interface is not abrupt. The contributions to the C 1s core level shift ~1eV to lower binding energy, while the relative ratio of the intensity of C 1s peaks changes, provides further evidence for changes in screening with aluminum doping within the polymer film. The XRD data also shows the crystalline structure of the copolymer film can be deformed with aluminum doping, if the polymer film is annealed.

Semiconductors

Room 306 - Session SC+EL+SS-ThM

Hydrogen On and In Semiconductors

Moderator: J.T. Yates, Jr., University of Pittsburgh

8:20am SC+EL+SS-ThM1 Step Structures and Energies on Vicinal Si(001) Monohydride Surfaces: Dependence on H Chemical Potential, A. Laracuente, L.J. Whitman, Naval Research Laboratory

It is well known that foreign adsorbates can alter the equilibrium step structure on surfaces and often have a dramatic effect on film growth. Given that most semiconductor devices are fabricated in hydrogen-rich environments on silicon substrates, a comprehensive understanding of how hydrogen affects Si step energies is essential to the development of accurate models of semiconductor growth and processing. We have determined the equilibrium step structures and step formation energies for the whole range of monohydride-terminated (001)-terrace-plus-step surfaces. Compared with the clean surfaces, hydrogen termination alters the atomic-scale step edge structure and, in many cases, causes large-scale changes in the surface morphology. The structural modifications result directly from a change in the relative energies of the possible single- and

double-layer step configurations. On nominal Si(001), the S@sub B@ steps are mostly non-rebonded and rougher after H passivation. A kink distribution analysis reveals that H reduces the nearest neighbor interaction across the S@sub B@ steps by an order of magnitude. Whereas the nearest neighbor interaction strongly depends on H@sub 2@ pressure, i.e. the H chemical potential, the step formation energies do not. On D@sub B@-stepped surfaces, such as Si(1 1 11), a statistical analysis of the steps shows that H lowers the formation energy of non-rebonded D@sub B@ and S@sub B@ steps, making them close in energy to the rebonded D@sub B@ steps. Post annealing a monohydride Si(1 1 11) surface without H significantly changes the n-D@sub B@/r-D@sub B@ ratio, indicating that the D@sub B@ step formation energies strongly depend on H chemical potential.

8:40am SC+EL+SS-ThM2 Si(100) Surface Roughening and H Atom Absorption: Surface and Bulk Characterizations., S.K. Jo, J.H. Kang, Kyung Won University, S. Korea; X. Yan, J.M. White, J.G. Ekerdt, University of Texas at Austin; J. Lee, Seoul National University, S. Korea; J.Y. Maeng, S.H. Kim, Korea Advanced Institute of Science and Technology

Absorption of thermal-energy gaseous hydrogen atoms by Si(100), exceeding by far the dopant and other impurity concentrations, occurs within a narrow substrate temperature (T@sub s@) window centered at ~ 460 K. The absorbed hydrogen persists in the crystalline bulk as highly mobile species before migrating out and desorbing as molecular hydrogen at T@sub s@ as high as 900 K, well above the recombinative desorption temperatures of surface-adsorbed H. Developing and sustaining atomic-scale surface roughness, by H-induced silicon etching, is a prerequisite for H absorption and determines the T@sub s@ window. In support of these conclusions are our TPD, Raman, SIMS, TEM, and STM data for this fundamental and interesting phenomenon of thermal H atom absorption by Si(100).

9:00am SC+EL+SS-ThM3 Dissociation Pathways of Molecular Hydrogen on Silicon Surfaces@footnote 1@, U. Höfer, Philipps Universität Marburg, Germany INVITED

The dissociative adsorption of H@sub 2@ on Si(001) has emerged as a prototype for activated chemical reactions on semiconductor surfaces. One of the most distinctive features of this basic reaction is the low sticking probability for dissociative adsorption (< 10@super -11@) and the fact that thermally induced distortions of the Si lattice enhance the reactivity by many orders of magnitude. In order to reveal the atomic-scale motion responsible for "phonon assisted sticking" we have performed a series of experiments employing optical second-harmonic generation (SHG), supersonic molecular beam dosing, and scanning tunnelling microscopy (STM). It will be demonstrated that, similar to thermally activated dynamical distortions, the reactivity can be enhanced by static distortions of the surface by precoverage with atomic hydrogen or by steps. The barriers to adsorption at these well-defined sites were determined. They revealed systematic trends that could be reproduced by density functional calculations and traced back to the interplay between electronic structure and local distortions of the Si surface. We find that hydrogen adsorption proceeds via inter-dimer reaction pathways in all cases. Whenever the energy splitting between the reactive dangling-bond states of adjacent dimers may be reduced by low-energy displacements of Si atoms, the adsorption barrier is found to be low. @FootnoteText@ @footnote 1@ Work performed in collaboration with W. Brenig, A. Biedermann, M. Dürr, T. F. Heinz, M. Hilf, Z. Hu, P. Kratzer, E. Pehlke, M. B. Raschke and M. Scheffler.

9:40am SC+EL+SS-ThM5 Hydrogen Bonding on Compound Semiconductor Surfaces, R.F. Hicks, Q. Fu, University of California, Los Angeles; L. Li, University of Wisconsin, Milwaukee; C.H. Li, University of California, Los Angeles

Hydrogen adsorption on gallium arsenide and indium phosphide (001) surfaces has been studied by scanning-tunneling microscopy and internalreflection infrared spectroscopy combined with ab initio molecular cluster calculations. The calculations are based on a series of clusters that accurately simulate the group III and V dimer termination of the surface. Good agreement has been achieved between the vibrational frequencies predicted by the theory and those observed in the experiments. On the anion-rich surfaces, hydrogen adsorbs on arsenic (or phosphorous) dimers to form isolated and coupled monohydrogen bonds and dihydrogen bonds. Conversely, on the cation-rich surface, hydrogen adsorbs on gallium (or indium) dimers to form terminal and bridged metal hydrides. The latter species occur in isolated or coupled structures involving two or three metal atoms. The implications of these results for the surface science of compound semiconductors will be discussed at the meeting.

10:00am SC+EL+SS-ThM6 Scanning Tunneling Microscopy of Low Temperature Adsorption H2 on GaAs(001), *H. Xu*, National University of Singapore, Singapore; *Y. Lee, J. Lee, A. Lee*, National University of Singapore The variable temperature scanning tunneling microscope (VT-STM) has been used to study in-situ the transition of 2x6 reconstruction of GaAs (001) at low temperature. High resolution STM images show that the metastable As dimers rows of 2x6 reconstruction in GaAs (001) becomes unstable under the attack of the dissociated adsorption H@sub2@. As dimers were broken firstly due to the formation of double atom lines structure by the attacking of hydrogen on As dimers atoms. Furthermore, the opened As atoms rows on the top of this surface were twisted gradually up to coalesce together with a width of 3 As dimers. Unexpectedly, these compressed As atoms suddenly extend along the original As dimers rows direction(-110) gives rise to form a metastable trimer As rows.

10:20am SC+EL+SS-ThM7 Theoretical Approaches for Predicting SiGe Heteroepitaxy, C. Mui, S.F. Bent, C.B. Musgrave, Stanford University

The demand for silicon-germanium devices has been growing in recent years due to potential applications in areas such as infrared photodetection, wireless communications and guantum nanostructures. The need for improved SiGe processing has motivated efforts to better understand the detailed reaction mechanisms of SiGe heteroepitaxy, including the adsorption of gas phase precursors and the removal of hydrogen from SiGe surfaces. We have used Becke3LYP density functional theory to study the effect of Ge alloying on the energetics and kinetics of H2 desorption from SiGe surfaces. We have investigated H2 desorption from the Si-Si homodimer, the Si-Ge heterodimer and the Ge-Ge homodimer sites. We found that in the transition state the two desorbing hydrogen atoms are localized above one surface atom, such that the structure resembles a dihydride species. The transition states on all three types of dimers have similar geometries, independent of the identity of the surface dimer atoms. Furthermore, the activation barriers depend only on the identity of the dimer atom not bonded to the desorbing hydrogens. For example, the activation barrier for H2 desorption from the Si site of a Si-Ge heterodimer is lower than that from a Si-Si homodimer by 10.6 kcal/mol. However, the barrier for desorption from the Ge-Ge homodimer is the same as that from the Si site of a Si-Ge heterodimer. We also found that the activation barrier for H2 desorption is only affected by surface Ge, and not Ge in the bulk. Calculations on a three dimer cluster showed that the activation barriers are dependent on cluster size, indicating that charge transfer and surface strain play a role in the desorption process. Finally, we will present results concerning additional surface reactions including the adsorption of germane on SiGe surface dimers.

10:40am SC+EL+SS-ThM8 Real-time Monitoring of H@sub 2@ Adsorption on C(001) at High Temperature by Ultraviolet Photoelectron Spectroscopy, Y. Takakuwa, M. Asano, Tohoku University, Japan

The hydrogen-terminated diamond surface has attracted much attention not only as a high efficiency electron emitter because of its electron affinity being negative (NEA) but also as a p-type conductive surface for fieldeffect-transistor devices. On the other hand, H@sub 2@ desorption on the hydrogen-terminated diamond surface occurs appreciably at higher temperature than 900@super o@C. This suggests that during the synthesis of diamond thin films by chemical vapor deposition using hydrocarbon gases such as methane the diamond-growing surface could be terminated by hydrogen and therefore NEA, even though the growth temperature is as high as 800-1000@super o@C. In this study, the electron affinity, secondary electron emission and pinning position of the Fermi level during exposing a diamond C(001) surface to H@sub 2@ at 700@super o@C and 1x10@super -5@ Torr were investigated by a real-time monitoring method of ultraviolet photoelectron spectroscopy. It was observed that (1) molecular hydrogen not activated by a hot tungsten filament absorbs dissociatively on the C(001) surface, wile it takes about 120 min to cover wholly the surface with hydrogen; (2) the electron affinity decreases from +0.4 eV for the clean surface to a negative value when the hydrogen coverage is about 90%; (3) the Fermi level is positioned at 0.61 eV above the valence band maximum just when the diamond surface changes to NEA; (4) the secondary electron yield increase with the hydrogen exposure time even after the complete termination of the surface with hydrogen. On the basis of the observed results, the time evolution of the surface electronic state during the hydrogen adsorption on the C(001) surface is discussed.

11:00am SC+EL+SS-ThM9 Infrared Studies of Hydrogen on Diamond (100), J.N. Russell, Jr., Naval Research Laboratory; J. Hovis, R.J. Hamers, University of Wisconsin; G.T. Wang, S.F. Bent, Stanford University; M.P. D'Evelyn, General Electric CRD; J.E. Butler, Naval Research Laboratory

Hydrogen atoms play a critical role in the chemical vapor deposition of diamond thin films. Currently, hydrogen plasmas are used to produce reproducible, clean, smooth, diamond (100) single-crystal surfaces. The use of diamond films for microelectronic or surface acoustic wave devices requires a fundamental understanding of the diamond surface termination and its interaction with adsorbed species. The hydrogen terminated diamond (100) surface is comprised of two 2x1 domains of monohydride surface dimers. Using s- and p-polarized multiple internal reflection infrared spectroscopy, the symmetric and asymmetric stretches of the HCCH surface dimer are easily resolved and are compared to ab initio calculations of the frequencies. The thermal dependence of the CH stretches is monitored as a function of the anneal temperature. When the hydrogen terminated surface is covered with a condensed layer of physisorbed molecules, the surface CH vibrational frequency is significantly influenced. We discuss the implications of these observations.

11:20am SC+EL+SS-ThM10 Fundamental Connection Between the ESD of H/D at Silicon Surfaces and at Oxide/Silicon Interfaces, K. Cheng, J. Lee, Z. Chen, J.-P. Leburton, E. Rosenbaum, K. Hess, J.W. Lyding, University of Illinois, Urbana-Champaign

Parallels can be drawn between electron stimulated desorption (ESD) of hydrogen at silicon surfaces in UHV and the ESD of hydrogen at the oxide/silicon interface in CMOS transistors. In particular, the multiple carrier vibrational heating mechanism for ESD, and the giant hydrogen/deuterium isotope effect play important roles in interface degradation. In this paper we will present results demonstrating the primary role of channel hot carriers in the degradation of the oxide/silicon interface of transistors. Experiments performed on p-channel MOSEET's show essentially no isotope effect for the creation of interface traps when carriers are injected into the oxide. However, a large isotope effect, consistent with vibrational heating, is observed when carriers flow along the oxide/silicon interface. One key difference between a H-passivated silicon surface and a H-passivated oxide/silicon interface is that there is a distribution of Si-H bond strengths at the interface due to variations in the amorphous oxide matrix. Experimental results will be presented which directly measure this distribution as well as show its ramifications in terms of rapid interface trap creation. The significance of this study comes from the fact that it is still a widely held view that the dominant transistor degradation mechanisms arise from carrier injection into the oxide, and therefore will be scaled away as industry trends progress. However, by performing new experiments and using basic surface science as a setting for their interpretation, we are able to show that there are fundamental problems with this view. Our results are supported by the fact that even state-of-the-art 0.18mm, 1.5 V CMOS chips show hundreds times lifetime improvement when hydrogen is substituted by deuterium.

11:40am SC+EL+SS-ThM11 Depth-Resolved Determination of the Hydrogen Concentration at Buried SiO@sub 2@/Si(100) Interfaces by Resonant Nuclear Reaction Analysis, *M. Wilde*, *M. Matsumoto, K. Fukutani*, University of Tokyo, Japan; *Z. Liu, Y. Kawashima*, NEC Corp., Japan

Hydrogen at the SiO@sub 2@/Si interface has been discussed to affect the electronic performance of MOS diodes by influencing the density of states at the interface. Drastic improvements of the reverse current resistance were reported after H@sub 2@-annealing of such devices.@footnote 1@ In this study the hydrogen concentration at the SiO@sub 2@/Si interface is measured directly by a Nuclear Reaction Analysis (NRA, based on the @sup 1@H(@sup 15@N, @alpha@@gamma@)@sup 12@C reaction), and the influence of H@sub 2@-annealing is investigated. Oxidized Si(100) samples with SiO@sub 2@ films of (19.0 - 41.5 nm) thickness were studied. In the as-oxidized condition, H near the SiO@sub 2@/Si interface is identified at a concentration lower than 4x10@sup 19@ cm@sup -3@. In the NRA depth profiles of all samples the center of the near-interface H-distribution appears at a depth (5±1) nm shallower than the interface location determined by ellipsometry. While no H is found in the silicon substrate, hydrogen is accumulated in a several nm wide layer within the oxide film adjacent to the interface. This result supports the idea of a transition region between the mere interface and the SiO@sub 2@ material, where stoichiometry and strain-induced defects may act as local bonding sites for hydrogen. In-situ annealing of the oxidized wafers in ambient H@sub 2@ gas causes a substantial increase of the H-concentration near the SiO@sub 2@/Si(100) interface, whereas the width of the H-distribution and its

position within the oxide film remain unchanged. The H-distribution is thermally stable below the annealing temperature of 400@deg@C. On heating to higher temperatures in vacuum depletion of H from the interface layer occurs to a concentration level below the as-oxidized condition. Hydrogen can be replenished at the interface by repeating the H@sub 2@-annealing procedure. @FootnoteText@ @footnote 1@ S. Fujieda, H. Nobusawa, M. Hamada, T. Tanigawa, J. Appl. Phys. 84 (1998) 2732.

Dielectrics

Room 312 - Session DI+EL+MS-ThA

High K Dielectrics: Perovskites

Moderator: J.N. Kidder, University of Maryland

2:00pm DI+EL+MS-ThA1 High Density Thin Film Ferroelectric Nonvolatile Memories, R. Ramesh, University of Maryland INVITED

Over the past two years, we have focused considerable effort on understanding the deposition and characterization of conducting barrier layers for the direct integration of ferroelectric capacitors on a poly-Si plug. Our specific focus has been on the materials science of the barrier layers to understand the role of crystallinity and process parameters on the structural and chemical integrity of the barrier layers during the subsequent growth of the ferroelectric capacitor stack. We are using the PZT system with conducting oxide electrodes as a prototypical test system for which at least two different conducting barrier materials systems have been successfully developed. Using both epitaxial and polycrystalline capacitors on these conducting barriers as test vehicles, we have been carrying out systematic studies on the effect of composition, point defect chemistry, strain and other processing variables on the structural integrity and ferroelectric properties. A novel aspect of our work is the use of scanning electric force microscopy techniques to understand the microscopic influence of film microstructure on the ferroelectric properties. In this presentation, we will present results of our progress on the process integration, device properties, specifically, polarization switching and relaxation dynamics and microscopic observations of ferroelectric properties and time dependent changes ; stress effects on fundamental properties. This work is supported by the NSF-MRSEC under Grant No. DMR- 96-32521 and by Bellcore.

2:40pm DI+EL+MS-ThA3 Process Window Extension of TiN Diffusion Barrier using Pre-oxidation of Ru and RuO@sub x@ Film for (Ba,Sr)TiO@sub 3@ Dielectric Film, H.J. Kim, S. Kim, Hyundai Electronics Industries Co. Ltd., Korea

(Ba,Sr)TiO@sub 3@(BST) thin film and other high dielectric oxides have attracted considerable attention due to their possible application in dynamic random access memories. However, serious integration issues are faced with in many cases because BST films need to be grown at rather high deposition or post-annealing temperatures of above 600°C in an oxidizing ambient. Deterioration of capacitor performance may result from interdiffusion and oxidation. Therefore, a diffusion barrier for oxygen should be developed for high-density DRAM device. In order to extend the process window of conventional sputtered TiN diffusion barrier and find out a proper electrode, in this experiment, the effect of pre-annealing method on the oxidation behavior of TiN barrier during 2 step annealing for BST dielectric film. Rapid thermal annealing in oxygen ambient (RTO) and N@sub 2@O plasma oxidation was respectively introduced to form a thin RuO@sub x@ layer and bind between oxygen and Ru at the surface of each Bu and BuO@sub x@ film. It is expected that a thin BuO@sub x@ layer be formed at the surface of each film by RTO and N@sub 2@O plasma. This can be retarded the oxygen indiffusion through Ru and RuO@sub x@ layer at high temperature due to complex diffusion paths and strongly stuffed along the grain boundaries as well as matrix. Two steps annealing for BST dielectric film is recently introduced to minimize the oxidation of diffusion barrier. In this work, a role of thin RuO@sub x@ oxidized layer formed at the surface of each Ru and RuO@sub x@ film by different pre-annealing methods prepared with/without BST deposition is investigated during two steps annealing.

3:00pm DI+EL+MS-ThA4 Atomic Polarization and Screening Charge by Variable Temperature Scanning Probe Microscopy of Ferroelectric Surfaces, S.V. Kalinin, D.A. Bonnell, University of Pennsylvania

Atomic force microscopy (AFM), electrostatic force microscopy (EFM), scanning surface potential microscopy (SSPM) and piezoresponse imaging (PRI) are applied to the BaTiO3 (100) phase transition. The imaging mechanism for non-contact microscopies (EFM and SSPM) based on an analytical solution for potential and field above the surface is discussed. The PRI imaging mechanism on a ferroelectric surface is analyzed in terms of the solution of the combined electrostatic-piezoelectric indentation problem. The relationship between SPM signal and screened and unscreened charge density is established. Quantification of force and force gradient-distance dependencies indicate that polarization bound charge is screened on this surface when imaged in ambient environments. The

absolute value of the measured potential difference between domains of opposite polarity suggests that surface adsorbates play the governing role in surface potential. This conclusion is corroborated by a direct measurement of the phase transition and by observations of domain wall motion. The influence of tip shape effects and mobile surface charges on effective domain wall width is also discussed. The contribution of electrostatic forces to piezoresponse contrast is extracted from forcedistance measurements and its influence of the local hysteresis loops is estimated. Considerations regarding the polarization switching by the tip are presented. Based on the experimental observations for this and other systems the dominant role of electromechanical vs. electrostatic effects in PRI imaging mechanism is established.

3:20pm DI+EL+MS-ThA5 Film-formation Mechanisms, Microstructure, and Properties of BST Thin Films Grown By MOCVD, Y. Gao, Pacific Northwest National Laboratory INVITED

A review of MOCVD BST thin films will be presented, focusing on precursor chemistry, film-formation mechanisms, and relationship between film processing, microstructure and dielectric properties. In particular, the precursor chemistry and film-formation r eactions have been studied using isotopic labeling experiments (@super 18@O@sub 2@). The precursor chemistry was found to strongly depend on substrate materials. In an oxygen ambient, at least four different reaction processes involved the removal of carb on from the precursor ligands on oxide covered Pt(111). Time-of-flight secondary ion mass spectrometry reveals both M@super 18@O and M@super 16@O (M= Ba, Sr, Ti) in the BST films, indicating that the oxygen in the BST films originates from both the gas ph ase oxidants (@super 18@O), and the precursor ligands (@super 16@O). The ligand substitution by gas phase O@sub 2@ plays a more prominent role in the film-formation at lower temperatures. On the other hand, the reactive oxygen radicals produced by micr owave plasma involved more in breaking the O-C bonds than substituting the precursor ligands for the film formation, resulting in larger surface roughness. Use of the 50%@super 18@O@sub 2@-50%N@sub 2@@super 16@O mixture results in a reduction of @super 18@O incorporation in the BST films, indicative of the direct involvement of N@sub 2@O in the film-formation reactions. The mechanistic studies are essential for understanding the BST precursor properties, and provide useful information to correlate the fil m m icrostructure, step coverage, and dielectric properties with the precursor properties. In addition, the study shows that precursor reactivities strongly affect the step coverage on the 3D structure, but little effect on the microstructure, surface morphology, and dielectric properties of the stoichiometric BST films. These properties strongly depend on the film composition, substrate material, and growth temperature.

4:00pm DI+EL+MS-ThA7 Epitaxial (Ba,Sr)TiO@sub 3@ on MgO for Room Temperature Microwave Phase Shifters, *C.L. Chen, J. Shen, S.Y. Chen, C.W. Chu,* University of Houston; *F.W. Van Keuls, F. Miranda,* NASA Glenn Research Center; *J.C. Jiang,* Louisiana State University

Single crystalline ferroelectric Ba@sub 0.6@Sr@sub 0.4@TiO@sub 3@ thin films were epitaxially grown on (001) MgO by using pulsed laser ablation. Microstructure studies from x-ray diffraction and electron microscopy suggest that the as-grown films are c-axis oriented with their interface relationship of @sub BSTO@//@sub MO@. Edge dislocations were found through the entire interface in every 8 unit cell length. Microwave property measurements indicated that the room temperature coupled microwave phase shifter have achieved with phase shift over 200@super o@ at 23.675 GHz and a figure of Merit of about 55@super o@/dB. The room temperature dielectric constant and loss tangent were found to be 1688 and 0.008 and the tunability was 33% with 2.5V/ μ m. The result suggests that the performance of microwave phase shifter based on the epitaxial ferroelectric thin films on (001) MgO are closed to the practical applications in the wireless rf communications.

4:20pm DI+EL+MS-ThA8 High Temperature Etch Processing for FeRAM MFM Capacitor Stack Fabrication, *L.G. Jerde*, *A. Cofer*, *R.A. Ditizio*, *S. Marks*, *J.A. Meyer*, *K.A. Olson*, *S.P. DeOrnellas*, Tegal Corporation

The unique materials utilized in FeRAM MFM capacitor stacks present numerous integrated device fabrication challenges, particularly in the patterning of these materials and the capacitor stacks that utilize them. Many of these patterning challenges are due to the intrinsic involatility of the reaction products formed when etching the elemental constituents of the FeRAM materials (i.e., Pt, Ir, Pb, Zr, Sr and Bi). These challenges have been successfully met for several years by utilizing photoresist etch masks in conjunction with the plasma etch technologies of low pressure, high density and dual frequency. While this technological approach is extendible

for the foreseeable future of FeRAM capacitor stack definition, the intrinsic involatility of their etch reaction products has recently sparked wide spread interest in utilizing high temperature etch processes to meet the as yet undefined future requirements for these applications. Although there are benefits to this high temperature approach, there are also risks. Among these risks are a number of key considerations that must be dealt with to successfully develop and implement high temperature etch process solutions for FeRAM applications. The first set of these considerations is related to the requirement that the etch tool provides reliable wafer, as opposed to wafer chuck, temperature and temperature uniformity control. In view of the industry trend toward single mask, full stack processes, another set of considerations is the requirement that the etch tool be able to rapidly vary the wafer temperature to accommodate the optimum temperature for each of the FeRAM materials being used. Yet another set of considerations are those related to wafer temperature limitations imposed by the Perovskite structure transition temperature, device damage and thermal budget. We will discuss and illustrate these considerations and present selected high temperature etch process results for various FeRAM films and stacks.

Semiconductors

Room 306 - Session SC+SS+EL-ThA

III-Nitride Growth and Nucleation

Moderator: V.M. Bermudez, Naval Research Laboratory

2:00pm SC+SS+EL-ThA1 Kinetics of GaN Growth and Decomposition, D.D. Koleske, A.E. Wickenden, R.L. Henry, M.E. Twigg, J.C. Culbertson, Naval Research Laboratory INVITED

While many devices have been demonstrated in the group III nitrides, details of the chemical reaction mechanisms for producing high quality GaN using metallorganic vapor phase epitaxy (MOVPE) continues to be an active area of research. In this presentation, I will highlight the results from several kinetic studies of GaN growth. This will include investigations of GaN decomposition in a commercial MOVPE reactor at temperatures and pressures typically used for growth. The GaN decomposition rates were measured in H@sub 2@, N@sub 2@, mixed H@sub 2@ and N@sub 2@, and mixed H@sub 2@ and NH@sub 3@. From these studies an enhancement in the GaN decomposition rate is observed in pure H@sub 2@ and mixed H@sub 2@ and NH@sub 3@ flows as the reactor pressure is increased above 100 torr. @footnote 1@ The mechanism for enhanced GaN decomposition will be presented. Measurements of GaN growth (with trimethylgallium) and decomposition (without trimethylgallium) rates under otherwise identical conditions indicate the extent of decomposition and incorporation during growth. GaN decomposition also accounts for a decrease in the GaN nucleation at higher pressures during the initial high temperature growth. This decrease in the nucleation density leads to increased grain size and higher quality GaN films.@footnote 2@ Kinetic issues relating to incorporation of defects will also be presented. These issues include a growth model for stoichiometric GaN growth,@footnote 3@ and the kinetics of surface carbon removal. All work sponsored by the Office of Naval Research. @FootnoteText@ @footnote 1@ D.D. Koleske, et al., Appl. Phys. Lett. 73, 2018 (1998); ibid. 75, 1646 (1999). @footnote 2@ A.E. Wickenden, et al., J. Electron. Mat. 29, 21 (2000). @footnote 3@ D.D. Koleske, et al., J. Appl. Phys. 84, 1998 (1998).

2:40pm SC+SS+EL-ThA3 Carbonization of Si (111) by Gas Source Molecular Beam Epitaxy using Triethyl Gallium and Subsequent GaN Growth, E. Kim, A. Tempez, A. Bensaoula, University of Houston

Next to sapphire, SiC is the most commonly utilized substrate for GaN heteroepitaxy. In addition to a better lattice match it has the advantage of being available in either conducting or insulating form. The most desirable substrate from both processing and cost point of view is Si since it will allow direct integration of GaN-based devices with conventional Si technology. To that end many approaches have been attempted to overcome the lattice mismatch and nucleation issues for GaN deposition on Si. We have already reported on RF-MBE and chemical beam epitaxy (CBE) of GaN on Si(111) using AIN buffer layers and demonstrated LEDs from our materials. To further improve on our previous results we explored the use of SiC as a buffer layer for the growth of GaN on Si. In this paper we demonstrate deposition of GaN on a SiC buffer layer formed by in situ carbonization of Si using a metalorganic precursor (triethylgallium: TEG) as the carbon source. The carbonization of the Si (111) surface is identified using in-situ time of flight low energy ion scattering, ex-situ XPS and XRD. The thickness, the crystalline quality and the surface morphology of the

carbonized layer are found to be very temperature dependent. A 6H-SiC polycrystalline thin film is formed above 780°C. Layers formed at 800°C are thicker and rougher than those formed at 780°C. In either case, Ga is not incorporated into the SiC layer. The SiC layer is shown to efficiently block the formation of SiO@subx@N@suby@ surface species which hinders the GaN nucleation and makes GaN/Si heteroepitaxy non-reproducible. GaN layers deposited in the same reactor by CBE using TEG and ammonia were analyzed as a function of the SiC layer thickness and annealing temperature. Data from these layers as well as from RF-MBE GaN deposited on these SiC buffer layers will also be presented. This project was funded by a NASA cooperative grant #NCC8-127 to the Space Vacuum Epitaxy Center.

3:00pm SC+SS+EL-ThA4 Epitaxial III-V Nitride Growth on SiC(0001) by Means of A@super 3@@Sigma@@sub u@@super +@ Metastable Molecular Nitrogen, D.C. Jordan, D.J. Smith, I.S.T. Tsong, R.B. Doak, Arizona State University

High quality epitaxial III-N semiconductor films, ranging in thickness from 300 to 900 Å, have been grown using A@super 3@@Sigma@@sub u@@super +@ metastable nitrogen molecules. The work employed a corona discharge supersonic free-jet (CD-SFJ) to generate a molecular beam containing exclusively the A@super 3@@Sigma@@sub u@@super +@ activation state in an otherwise ground state N@sub 2@ beam. AlN films were grown on 6H-SiC(0001) and Si(001) substrates. GaN films were grown on the same substrates and on buffer layers of AIN deposited in situ on 6H-SiC(0001). The N-atom incorporation efficiency (defined as the number of N-atoms attaching to a III-N surface per incident metastable A@super 3@@Sigma@@sub u@@super +@ molecule) approached 100% in most instances and was found to be independent of substrate temperature from 600 to 900 ŰC, implying direct molecular chemisorption as the underlying reaction mechanism. These measurements support theoretical predictions that A@super 3@@Sigma@@sub u@@super +@ is an ideal precursor for III-N growth.

3:20pm SC+SS+EL-ThA5 Crystal Growth Kinetics and Transport in GaN Epitaxial Lateral Overgrowth, *M.E. Coltrin, C.C. Willan, M.E. Bartram,* Sandia National Laboratories INVITED

Epitaxial Lateral Overgrowth (ELO) is a useful technique to improve material quality and reduce defects in GaN. In ELO, a mask pattern of dielectric material, usually either silicon nitride or silicon dioxide, is deposited on top of a GaN buffer layer. Further growth of GaN occurs selectively on exposed areas of the underlying buffer layer, and not on the dielectric material. Typically, ELO conditions are optimized for a maximum lateral - to - vertical growth rate ratio. Growth kinetics of GaN crystal faces and transport effects will be discussed in this paper. Dimensions of the exposed and masked areas in line and dot patterns, pattern orientation with respect to the underlying substrate, and growth time were systematically varied. Growth rate information was obtained from scanning electron microscope (SEM) measurements. The coupling between transport and kinetic effects was examined by means of 2-D and 3-D numerical simulations. In general, transport of material from the masked to the unmasked regions is quite efficient. However, ELO deposition growth efficiency is shown to decrease dramatically when the ratio of exposed to masked areas becomes very small. ELO experiments incorporating deep trenches will be described, which are designed to distinguish between lateral transport of material via gas-phase vs. surface diffusion. Gas-phase transport of material appears to dominate. We have found a quantitative way to translate results from different pattern dimensions into a pseudo time basis by scaling growth features by a length scale W, the size of the exposed deposition window.

4:00pm SC+SS+EL-ThA7 Thick GaN on Si Substrate by Hydride Vapor Phase Epitaxy using Epitaxial Lateral Overgrowth Technique, J.W. Lee, J.B. Yoo, Sungkyunkwan University, Korea

The thick GaN growth is a very essential issue for the fabrication of GaN substrate. Epitaxial lateral overgrowth (ELOG) is one of the promising techniques for the high quality GaN epilayer as a fabrication of optical and electronic devices. In this study, two-step growth of GaN was optimized to grow high-quality GaN. First, we attempt ELOG technique for growth of GaN on a Si(111) substrate by MOCVD. Then the thick GaN film was overgrown on ELOG GaN by HVPE. Because of their large lattice mismatch between GaN and Si, the use of an intermediate layer or buffer layer is essential. For the growth of GaN on Si substrate the AlN layer was used to buffer layer. The AlN buffer layer was deposited by RF sputtering. The LT-GaN by was induced another buffer layer on Si substrate. The ELOG GaN on Si substrate was grown by MOCVD. The TMGa and ammonia were used as

source gases. The growth temperature of ELOG GaN was changed range in 500°C to 1100°C. The thick GaN was grown by conventional HVPE. The chlorinated gallium and ammonia were used as source gas for Ga and N, respectively. The growth temperature of thick GaN was varied from 800°C to 1100°C. The SiO@sub 2@ was grown by PECVD for the use of ELOG mask on buffer layers. The stripe pattern was developed along and crystal axis of GaN. The various stripe windows with a different spacing between stripes were developed on the SiO@sub 2@ mask by conventional photolithography and wet chemical etching. The effect of growth parameters such as AIN, LT-GaN, growth temperature, stripe patterned direction were investigated. Surface roughness and morphologies of ELOG GaN film were analyzed by atomic force microscopy (AFM) and scanning electron microscope (SEM). The effect of ELOG on thick GaN-film was characterized by double crystal x-ray diffractometer (DCXRD), low temperature photoluminescence (PL) and transmission electron microscope (TEM).

4:20pm SC+SS+EL-ThA8 Growth and Electronic Structure of ScN, a New Refractory III-V Semiconductor, D. Gall, I. Petrov, J.E. Greene, University of Illinois, Urbana

ScN layers, 40 to 345 nm thick, were grown on MgO(001) substrates at 750 °C by ultra-high-vacuum reactive unbalanced magnetron sputter deposition in pure N@sub 2@ discharges at 5 mTorr. All films were stoichiometric with N/Sc ratios of 1.00±0.02. Microstructural and surface morphological evolution were found to depend strongly on the energy E@sub i@ of N@sub 2@@super +@ ions incident at the film surface during deposition. Nucleation and the initial growth of ScN layers deposited with E@sub i@ = 13 eV are dominated by the formation of 111 and 002-oriented islands which exhibit local epitaxy. However, preferred orientation rapidly evolves toward a purely 111 texture by a film thickness of ~50 nm as 002 grains grow out of existence in a kinetically-limited competitive growth mode. In distinct contrast, ScN layers deposited with E@sub i@ = 20 eV are single crystals which grow in a cube-on-cube epitaxial relationship with MgO(001). ScN optical properties were determined by transmission, reflection, and spectroscopic ellipsometry while in-situ x-ray and UV valence-band photoelectron spectroscopy were used to determine the density of states (DOS) below the Fermi level. The measured DOS exhibits peaks at 3.8 and 5.2 eV stemming from the N 2p bands and at 15.3 eV due to the N 2s bands. The imaginary part of the measured dielectric function @epsilon@@sub 2@ consists of two primary features due to direct X- and @GAMMA@-point transitions at photon energies of 2.7 and 3.8 eV, respectively. The ScN band structure was calculated using an ab initio Kohn-Sham approach which treats the exchange interactions exactly within density-functional theory. Combining experimental and computational results, we show that ScN is a semiconductor with an indirect @GAMMA@-X bandgap of 1.3±0.3 eV and a direct X-point gap of 2.4±0.3 eV.

4:40pm SC+SS+EL-ThA9 Structure and Optical Properties of ScN(001) Grown by Molecular Beam Epitaxy, H. Al-Brithen, A.R. Smith, W.M. Jadwisienczak, H.J. Lozykowski, Ohio University

Scandium nitride is grown by molecular beam epitaxy on MgO(001) substrates. Reflection high energy electron diffraction and x-ray diffraction both confirm the (001)-orientation of the ScN layer. The measured lattice constant is in close agreement with the expected lattice constant a = 4.501Å, and there is no sign of strain aside from that due to differential thermal contraction between film and substrate during cooling. As measured by atomic force microscopy and scanning tunneling microscopy (STM), these films are found to be smooth, with terraces separated by steps of height a/2. As the Sc flux is varied, the growth morphology also varies - from that of plateaus and pyramids (for lower Sc flux) to that of spiral mounds (for higher Sc flux). We associate the transition with a particular ratio of Sc flux to N flux. Films grown with a lower Sc/N flux ratio have a distinct reddish appearance, and a turn-on feature at 570 nm in the cathodoluminescence (CL) spectrum is measured, consistent with a band gap energy of about 2.2 eV. Films grown with higher Sc/N flux ratio are dark in appearance, and no turn-on feature at 570 nm is observed in the CL spectrum. STM images atomically resolve the rock-salt surface lattice for films grown with lower Sc/N flux ratios; however, for films of higher Sc/N flux ratio, small protrusions are observed on the terraces, which are most likely excess Sc atoms. The effect of the Sc/N flux ratio on the stoichiometry of the films will also be discussed.

5:00pm SC+SS+EL-ThA10 ScN Thin Films and Thin Film Devices, *X. Bai, M.E. Kordesch*, Ohio University

ScN films have been grown by plasma assisted physical vapor deposition (PAPVD) and reactive sputtering on quartz, sapphire, silicon and MgO.

Growth temperature ranges from 300K to 1100K, thickness ranges from 50nm to 800nm. For PAPVD films, the XRD results show that ScN grows with (111) texture on quartz, both ScN (111) and (200) textures are observed on sapphire (0001), and (200) textured growth on Si (100). ScN films grown at 300 K are amorphous. Sputtered films show both (111) and (200) texture under various conditions. ScN grows epitaxially on MgO (100). Measurement of the lattice constant ranges from 0.442 nm on quartz to 0.458 nm on silicon. Temperature dependent condcutivity measurements show that ScN is a semiconductor. Intrinsic, p type and n type ScN can be synthesized, with carrier concentrations between 10@super12@ cm@super-3@ to 10@super22@cm@super-3@. The index of refraction is determined from IR measurements to be 2.46 ± 5%. The best optical bandgap result from our measurements is 2.26 eV. There are theoretical predictions of an indirect gap at about 1 eV, outside of our measurement range. ScN films have been used to fabricate p-n junctions, junctions with p and n type Si, and lattice mismatched isotype n-n junction with GaN. Functional ohmic contacts to ScN have been fabricated using Ti, Pd and Ni.

Friday Morning, October 6, 2000

Semiconductors Room 306 - Session SC+EL-FrM

III-Nitride Processing and Devices

Moderator: D.D. Koleske, Naval Research Laboratory

8:20am SC+EL-FrM1 Process Development For Small-Area GaN/AlGaN HBTs, K.P. Lee, G. Dang, A.P. Zhang, F. Ren, University of Florida; J. Han, Sandia National Laboratories; W.S. Hobson, Lucent Technologies, Bell Laboratories; C.R. Abernathy, S.J. Pearton, University of Florida; J.W. Lee, Plasma Therm

A self-aligned fabrication process for small emitter contact area (2x4 μ m@super 2@) GaN/AlGaN heterojunction bipolar transistor is descried. The process features dielectric-spacer sidewalls, low damage dry etching and selected-area regrowth of GaAs(C) on the base contact. The junction I-V characteristics were evaluated at various stages of the process sequence and provided an excellent diagnostic for monitoring the effect of plasma processes such as CVD or etching. A comparison will be given with large emitter-area (2.5x10@super 4@ μ m@super 2@) devices fabricated on the same material. The small-area devices are alternative for microwave power switching applications.

8:40am **SC+EL-FrM2 Morphology on HDP-Etched III-Nitride Materials**, *T.-N. Kuo, J.-H. Yeh, H.-J. Lee, C.-A. Chen, D.G.-K. Jeng*, Nano-Architect Research Corporation, Taiwan

Needle-shaped morphology or highly textured surface was often observed after GaN/GaInN multiple layered structures have been etched in highdensity plasma; this phenomenon was not so often observed in structures containing GaN alone. It is attributed to layers containing indium under certain chemical environments. An experimental procedure was carried out for the characterization of materials etching. It turned out that the needle-shaped morphology or textured surface was possibly the consequence of a micro-masking effect due to low-vapor pressure compound formed on the etched surface, which prohibits underneath layers from being etched. The experiments were conducted in a high-density plasma equipment with a novel plasma source designed exclusively by the authoring group. This equipment has the capability for a typical etch-rate of 7000-8000 Å/min for all types of III-nitride compound materials and structures with good surface morphology.

9:00am SC+EL-FrM3 Effects of Etch Processing on Contacts to n-GaN, *R. Singh*, *C.R. Eddy*, *Jr.*, Boston University; *H.M. Ng*, Lucent Technologies; *T.D. Moustakas*, Boston University

We report studies on the effects of high density plasma etching on the properties of ohmic contacts to n-GaN. Samples deposited by plasmaassisted MBE on a-plane sapphire and doped with Si are used in this study. Inductively coupled high density chlorine plasmas are applied to etch the surfaces of GaN and subsequent contacts (Ti/Al) to these etched surfaces are evaluated. We identify degradation of contact ohmicity even for very low rf bias powers (ion energies) as a function of the doping level in the GaN film. For films of high doping levels (3x10@super 18@ cm@super -3@), as might be encountered in a laser or LED structure, the degree of contact degradation, compared to the control sample, is a modest factor of 2 (4x10@super -4@ @ohm@cm@super -2@ to 1x10@super -3@ @ohm@cm@super -2@). However, for lower doping level films (10@super 17@ cm@super -3@), as might be encountered in electronic devices, the specific contact resistance is higher by almost two orders of magnitude for the same treatment (5x10@super -3@ @ohm@cm@super -2@ to 2x10@super -1@ @ohm@cm@super -2@). These as-deposited contacts are then rapid thermal annealed (700°C) in a nitrogen atmosphere, where specific contact resistance is monitored as a function of annealing time. Although there is improvement in contact resistivity, the effect of plasma exposure is still evident even at a cumulative rapid thermal annealing time of 280 seconds. We show that even modest ion energies in highly reactive chemistries can lead to contact degradation and that care must be taken in applying such processes if highly efficient power devices are to be routinely realized. In an effort to identify the cause of the degradation, we will also report SEM, AFM and surface sensitive photoluminescence measurements of the as etched surfaces. We will also discuss in-situ and ex-situ efforts to eliminate such degradation.

9:20am SC+EL-FrM4 Growth of Ga(In)NAs/GaAs Alloys by Plasma-Assisted Molecular Beam Epitaxy, A.L. Holmes, Jr., University of Texas at Austin INVITED

In recent years, the addition of nitrogen into GaInAs, created via energetic nitrogen species from a RF-plasma or decomposition of hydrazine-based precursors, has attracted a great deal of interest due to the large negative bowing parameter of the resultant semiconductor alloy. As a result, GaNAs/GaAs and GaInNAs/GaAs heterostructures can be grown which emit light at wavelengths applicable for lasers and detectors for fiber-optic communications or absorb wavelengths which make solar cells more efficient. While nitrogen leads to a significant reduction in the band gap of the resultant material, the addition of nitrogen (on the order of a few atomic percent) also leads to a significant reduction in luminescence intensity which has significant consequences for optoelectronic devices. In this talk, growth of the GaInNAs/GaAs alloy system will be discussed. The effects of important growth-related parameters such as growth temperature, RF plasma conditions, indium composition, and arsenic overpressure will be described. The resultant materials are characterized by xray diffraction, photoluminescence, and SIMS to create a picture of how nitrogen is incorporated and how this incorporation affects the resultant material properties. These properties are then compared to GaNAs-based photodetectors which show outstanding device performance with nitrogen concentrations as high as 2.5%.

10:00am SC+EL-FrM6 Field Electron Emission and Surface Properties of asgrown and Modified AlGaN Films, A. Bensaoula, I. Berishev, E. Kim, University of Houston; M. Ugarov, V. Ageev, E. Loubnin, A. Karabutov, General Physics Institute, Russia; A. Tempez, University of Houston

The correlation between surface morphology and composition, Si substrate orientation and field emission properties of Al@sub x@Ga@sub1-x@N and GaN/AIN films was investigated. It was demonstrated that a high Ga surface density provides thin films with better field electron emission characteristics such as a higher emission current and lower voltage threshold. It was found that a proper choice of the substrate orientation is crucial to obtaining the desired electronic properties since it plays a major role in the resulting thin film surface microstructure. A post-growth modification by X-ray irradiation was also performed on these films. Our results show a significant improvement in the field emission characteristics of the Al@sub x@Ga@sub1-x@N surfaces. The threshold field was reduced by up to three times and current density increased up to 10 A/cm@super2@. These results are consistent with data previously obtained for field emission and laser photoconductivity enhancement by Xray irradiation of BN thin films. The effect of the X-ray induced generation of additional density of states in the nitride material band gap, on the changes in film conductivity and surface potential barrier height will be discussed. The project was funded in part by a CRDF Grant assistance program (Project # RPO-698), a Russian Federation for Basic Research grant (# 99-02-16653) and a NASA Cooperative agreement #NCC8-127 to the Space Vacuum Epitaxy Center.

10:20am SC+EL-FrM7 Effect of Annealing and Carbon Concentration on the PL Intensity from GaN:Er and GaN:Eu, *M.E. Overberg, C.R. Abernathy, S.J. Pearton,* University of Florida; *J.M. Zavada,* U.S. Army European Research Office, UK

An attractive alternative for emission in the visible and near-IR are rare earth doped III-Nitrides, whose emission wavelength is host-material insensitive and less susceptible to thermal quenching than conventional narrow gap semiconductors. GaN doped with Er and Eu during growth by molecular beam epitaxy (MBE) has been found to produce strong room temperature emission at 1540 nm and 621 nm, respectively. In addition to the electronic characteristics of the host material, impurities such as C and H are expected to play an important role in the emission process. In this study, the effects of carbon doping and annealing in either nitrogen or forming gas on the luminescence intensity from Er-doped and Eu-doped GaN has been investigated. In samples with no added carbon, annealing was found to decrease the room temperature emission. The addition of carbon to the GaN during growth however, not only improved emission relative to non-carbon doped material but also produced material which improved with annealing. For carbon co-doped material the presence of hydrogen in the annealing ambient produced the greatest improvement in emission intensity, suggesting that both C and H are beneficial to the emission process. The effect of annealing on surface morphology and structural quality will also be presented as will a model for the observed PL behavior.

Friday Morning, October 6, 2000

10:40am SC+EL-FrM8 Probing Nanoscale Electronic Properties in Nitride Semiconductor Heterostructures, E.T. Yu, K.V. Smith, X.Z. Dang, University of California, San Diego INVITED

III-V nitride heterostructures are of outstanding current interest for both optoelectronic and electronic device applications. However, the high concentrations of point and extended defects typically present even in device-quality nitride semiconductor material necessitates detailed characterization and understanding of local structure and electronic properties at atomic to micron length scales for optimization of device performance. In particular, the presence of a variety of defect structures in combination with strong piezoelectric and spontaneous polarization effects in nitride semiconductors leads to pronounced variations in local electronic properties. Experimental characterization, theoretical analysis, and numerical simulation of these effects, especially in the context of nitride heterostructure field-effect transistor (HFET) structures, will be described. Scanning capacitance microscopy has been used extensively to characterize local electronic structure in AlGaN/GaN HFET structures. Measurement and analysis of capacitance contrast as a function of bias voltage allows submicron-scale lateral variations in transistor threshold voltage, nanoscale depleted regions within the channel of the transistor in the vicinity of negatively charged threading dislocations, and evidence of piezoelectric fields arising from local strain in the vicinity of dislocation lines to be observed. Application of large bias voltages during the imaging process is found to give rise to localized trapping of charge in deep levels. Measurement and analysis of the resulting contrast allows the distribution of trapped charge both laterally and as a function of depth to be probed.

11:20am SC+EL-FrM10 GaN and AlGaN Power Rectifiers, A.P. Zhang, G. Dang, F. Ren, X.A. Cao, K.P. Lee, S.J. Pearton, University of Florida; J. Han, Sandia National Laboratories; J.I. Chyi, National Central University, Taiwan; C.M. Lee, C.C. Chuo, National Central University, Taiwan

We fabricated the GaN & AlGaN rectifiers and p-i-n rectifiers on a range of different MOCVD-grown materials. The reverse breakdown voltages of lateral GaN&AlGaN rectifiers on 3µm thick resistive GaN&AlGaN were in a range of 2.3~4.3kV with a 30um Schottky metal and Ohmic metal spacing. The p-i-n diodes on 4µm thick GaN epitaxial layer showed a reverse breakdown voltage of 500V with turn-on voltage of ~5V (100A/cm@super 2@). Different edge termination methods were used to improve the performance of GaN rectifiers, including Schottky metal overlap, guard rings, and float rings and junction barrier control (JBS). The edge termination has a strong effect to prevent catastrophic breakdown at the contact periphery. The lowest R@sub ON@ was 0.14 @ohm@.cm@super 2@ for GaN rectifiers and 2.6 @ohm@.cm@super 2@ for AlGaN rectifiers. Figure-of-merit (V@sub RB@)@super 2@/R@sub ON@ are in the 6 -55 MW.cm@super -2@ range, emphasizing the potential of these devices for power switching applications. For the devices we fabricated, we invariantly observed the negative temperature coefficient for V@sub RB@ most likely due to the influence of defects in the heteroepitaxial GaN. For the similar reverse breakdown voltage, current densities are higher in the p-i-n structures, at the expense of higher turn-on voltage, but the on-voltages still need improvement in the Schottky rectifiers. A comparison will be given with state-of-the-art Si and SiC power rectifiers.

11:40am SC+EL-FrM11 Growth and Characterization of Gadolinium Oxide Gate Dielectric on Gallium Nitride, B.P. Gila, K.N. Lee, K.K. Harris, W. Johnson, V. Krishnamoorthy, C.R. Abernathy, F. Ren, S.J. Pearton, University of Florida

Fabrication of high performance metal oxide semiconductor field effect transistors (MOSFETs) on gallium nitride will require both good interfacial electrical characteristics and good thermal stability. While dielectrics such as SiO@sub 2@ and GaGdO have demonstrated low to moderate interface state densities, questions remain about their thermal stability and reliability, particularly for use in high power or high temperature widebandgap devices. In this talk we will discuss the utility of gadolinium oxide, Gd@sub 2@O@sub 3@, as a gate dielectric material on GaN. Gadolinium oxide deposited by gas source molecular beam epitaxy from elemental Gd and an electron cyclotron resonance (ECR) oxygen plasma has been found to produce layers with excellent surface morphologies as evidenced by SEM and AFM, with a surface roughness of less than 1 nm. Surface preparation techniques, both in-situ and ex-situ, have been explored to produce films of different crystal morphologies as evidenced by RHEED and TEM. Stoichiometric films can be easily obtained over a range of growth temperatures, growth rates and oxygen flows. This talk will describe the relationship between deposition conditions and film characteristics for Gd@sub 2@O@sub 3@, and will present electrical

characterization and thermal stability of capacitors fabricated from Gd@sub 2@O@sub 3@ on GaN.

— A —

Abelson, J.R.: EL-TuP2, 15; SC+EL+SS-WeP26, 28 Abernathy, C.R.: SC+EL-FrM1, 44; SC+EL-FrM11, 45; SC+EL-FrM7, 44 Adams, J.A.: SC+EL+SS-MoA7, 4 Ageev, V.: SC+EL-FrM6, 44 Aivazov, A.A.: SC+EL+SS-WeP5, 24 Akhadov, E.A.: OF-WeP11, 23 Akiyama, H.: SS2+NS+BI+EL-TuM7, 10 Al-Brithen, H.: SC+SS+EL-ThA9, 43 Alexander, C.: MI+EL-WeM8, 20 Altman, E.I.: SC+EL+SS-MoA6, 3 Ambrose, T.F.: MI+EL-WeM6, 20 Amirtharaj, P.: SC+EL+SS-WeA8, 32 Andersson, A.S.: BI+EL-TuA3, 11 Ang, T.C.: DI+EL+MS-WeM4, 18; DI+EL+MS-WeM6, 18 Antoniadis, H.: OF+EL+SS-WeM1, 20 Appenzeller, J.: EL+NS-TuA6, 12 Applegate, B.: EL+NS-TuM11, 7 Arena, D.A.: SS2+EL-MoA5, 5 Arnold, R.: SS2+NS+BI+EL-TuM1, 9 Asano, M.: SC+EL+SS-ThM8, 39 Asbalter, J.: SC+EL+SS-WeA8, 32 Aspnes, D.E.: DI+EL+MS-ThM3, 35; DI+EL+MS-ThM4, 35 Atwater, H.A.: EL+NS-TuA7, 12 Avouris, Ph.: EL+NS-TuA6, 12 — B — Backhed, F.: BI+EL-TuA3, 11 Bae, J.W.: SC+EL+SS-WeP17, 26 Bahierathan, B.: SC+EL+SS-WeA3, 31 Bai, X .: SC+SS+EL-ThA10, 43 Baranauskas, V.: EL-TuP8, 16; EL-TuP9, 16 Bartram, M.E.: SC+SS+EL-ThA5, 42 Bartynski, R.A.: SS2+EL-MoA4, 5 Barvosa-Carter, W.: SC+EL+SS-TuM1, 7 Baskaran, S.: DI+EL+MS-WeM1, 18 Beernink, G.: OF+EL+SS-ThM1, 37 Begarney, M.J.: SC+EL+OF-TuA5, 13; SC+EL+SS-TuM5, 8 Bell, L.D.: EL+NS-TuA7, 12 Beltrones, J.S.: EL-TuP12, 16 Bennett, B.R.: MI+EL-WeA6, 31; MI+EL-WeM3, 19; SC+EL+SS-TuM10, 8 Bensaoula, A.: SC+EL-FrM6, 44; SC+SS+EL-ThA3. 42 Bent, S.F.: SC+EL+OF-TuA3, 13; SC+EL+OF-TuA8, 14; SC+EL+SS-ThM7, 39; SC+EL+SS-ThM9.40 Berdnikov, A.A.: SC+EL+SS-WeP5, 24 Berfeld, M.: OF-WeP4, 22 Berishev, I.: SC+EL-FrM6, 44 Bermudez, V.M.: TF+EL-WeA9, 34 Bertagnolli, E.: DI+EL+MS-WeM8, 19 Bevan, M.: SC+EL+SS-WeP23, 27 Bezryadin, A.: EL+NS-TuM9, 7 Bhat, K.N.: DI+EL+MS-ThM10, 36 Bhat, V.K.: DI+EL+MS-ThM10, 36 Bhattacharyya, R.N.: SC+EL+SS-WeA9, 32 Biedermann, A.: SC+EL+SS-WeP7, 25 Birkner, A.: OF+EL+SS-ThM1, 37 Birnbaum, J.: DI+EL+MS-WeM1, 18 Blanchard, P.: OF+EL+SS-ThM5, 37 Blochwitz, J.: OF-WeP3, 22 Boag, N.M.: SC+EL+SS-WeP2, 24 Boer, E.: EL+NS-TuA7, 12 Boland, T.: BI+EL-TuA4, 11 Bonnell, D.A.: DI+EL+MS-ThA4, 41 Boo, J.-H.: SC+EL+SS-WeP16, 26 Boone, T.: DI+EL+MS-ThM5, 35 Borca, C.N.: OF+EL+SS-ThM11, 38 Boschetti, A.: OF+EL+SS-ThM6, 37

Bold page numbers indicate presenter

Bostwick, A.: SC+EL+SS-MoA7, 4 Böttcher, A.: TF+EL-WeA4, 33 Bracco, G.: SS2+NS+BI+EL-TuM3, 9 Bracker, A.S.: MI+EL-WeA6, 31; SC+EL+SS-TuM10.8 Bradley, D.D.C.: OF+EL+SS-WeM1, 20 Brongersma, M.L.: EL+NS-TuA7, 12 Bu, H.: SC+EL+SS-WeP23, 27 Buck, M.: SS2+NS+BI+EL-TuM2, 9 Budaguan, B.G.: SC+EL+SS-WeP5, 24 Budiman, R.A.: SC+EL+SS-WeA3, 31 Burger, A.: SC+EL+SS-WeA9, 32 Burnett, D.J.: SS2+NS+BI+EL-TuM8, 10 Busnaina, A.A.: SC+EL+SS-WeP9, 25 Butcher, M.J.: SC+EL+SS-TuM2, 7 Butler, J.E.: SC+EL+SS-ThM9, 40 Byeon, S.-C.: MI+EL-WeM8, 20 Byun, K.-R.: SC+EL+SS-WeP27, 28 - C -Cahill, D.G.: SC+EL+SS-WeA4, 32 Caldwell, M.L.: SC+EL+SS-WeP18, 26 Camillone III, N.: SC+EL+SS-TuM11, 8; SC+EL+SS-TuM7, 8 Campbell, A.J.: OF+EL+SS-WeM1, 20 Cao, X.: SC+EL+OF-TuA7, 14 Cao, X.A.: SC+EL-FrM10, 45 Carlsson, S.: EL+NS-TuA5, 12 Carr, D.: MI+EL-WeM2, 19 Carr, D.W.: EL+NS-TuM5, 6 Carter, R.J.: DI+EL+MS-ThM9, 36 Ceragioli, H.J.: EL-TuP9, 16 Ceyer, S.T.: SC+EL+SS-WeP6, 24 Chabal, Y.J.: DI+EL+MS-ThM1, 35; DI+EL+MS-ThM5, 35; DI+EL+MS-ThM7, 36; SC1+EL+SS-MoM2, 1; SC1+EL+SS-MoM8, 2 Chaban, E.E.: DI+EL+MS-ThM1, 35; SC1+EL+SS-MoM8, 2 Chambers, J.J.: DI+EL+MS-WeA10, 30 Chan, K.: EL+NS-TuA6, 12 Chan, L.H.: SC+EL+SS-MoA6, 3 Chaney, J.A.: OF+EL+SS-ThM9, 38 Chang, E.-G.: EL-TuP11, 16 Chang, J.P.: DI+EL+MS-ThM7, 36; DI+EL+MS-WeA6, 29 Chang, P.: EL-TuP16, 17 Chantis, A.N.: MI+EL-WeA7, 31 Chao, Y.C.: SC+EL+SS-WeP11, 25 Chayahara, A.: SC+EL+SS-WeP14, 26 Chen, C.-A.: SC+EL-FrM2, 44 Chen, C.L.: DI+EL+MS-ThA7, 41 Chen, D.: EL+NS-TuA9, 13 Chen, J.: EL+NS-TuM3, 6 Chen, L.C.: MI+EL-WeA3, 30; MI+EL-WeM1, 19 Chen, S.Y.: DI+EL+MS-ThA7, 41 Chen, Z.: SC+EL+SS-ThM10, 40 Cheng, C.-L.: EL-TuP1, 15; EL-TuP16, 17 Cheng, K.: SC+EL+SS-ThM10, 40; SC+EL+SS-WeP3, 24 Cheng, S.-F.: MI+EL-WeA6, 31 Cheong, H.-D.: MI+EL-WeM3, 19 Chernomordic, V.D.: SC+EL+SS-WeP5, 24 Chesterfield, R.J.: OF+EL+SS-WeM3, 21 Cho, E.: OF+EL+SS-ThM10, 38; SC+EL+SS-MoA8, 4 Cho, H.: SC+EL+SS-WeP13, 26 Cho, S.: OF+EL+SS-ThM10, 38; SC+EL+SS-MoA8, 4 Choi, J.: EL-TuP15, 17 Choi, K.-S.: SC+EL+SS-WeP27, 28 Choi, N.: SS2+NS+BI+EL-TuM4, 9 Choi, S.: EL-TuP5, 15 Choi, S.-K.: EL-TuP11, 16 Christman, S.B.: DI+EL+MS-ThM1, 35

Chu, C.W.: DI+EL+MS-ThA7, 41 Chu, S.N.G.: SC+EL+SS-WeP13, 26 Chung, K.W.: DI+EL+MS-WeM7, 19 Chung, M.Y.: OF-WeP1, 22 Chuo, C.C.: SC+EL-FrM10, 45 Chwang, A.B.: OF+EL+SS-WeM3, 21 Chye, Y.: MI+EL-WeM7, 20 Chyi, J.I.: SC+EL-FrM10, 45 Clevenger, L.: SC+EL+SS-WeP15, 26 Cofer, A.: DI+EL+MS-ThA8, 41 Collins, R.W.: TF+EL-WeA7, 34 Coltrin, M.E.: SC+SS+EL-ThA5, 42 Conard, T.: DI+EL+MS-ThM9, 36 Conrad, H.: TF+EL-WeA4, 33 Coulter, S.K.: SC+EL+OF-TuA7, 14; SC+EL+OF-TuA9, 14; SC+EL+SS-WeP1, 23 Coyle, C .: DI+EL+MS-WeM1, 18 Craighead, H.G.: BI+EL-TuA7, 11 Crowell, J.E.: SC1+EL+SS-MoM5, 1 Cruden, B.A.: TF+EL-WeA2, 33 Cruz, A.F.: EL-TuP12, 16 Culbertson, J.C.: SC+EL+SS-TuM10, 8; SC+SS+EL-ThA1, 42 — D — Dang, G.: SC+EL-FrM1, 44; SC+EL-FrM10, 45 Dang, X.Z.: SC+EL-FrM8, 45 D'Arcy-Gall, J.: SC+EL+SS-WeA6, 32 de Vries, S.: EL+NS-TuM9, 7 Dekker, C.: EL+NS-TuM9, 7 del Alamo, J.A.: EL+NS-TuA6, 12 Delerue, C.: OF+EL+SS-ThM5, 37 Demchenko, D.O.: MI+EL-WeA7, 31 Deng, W.-L.: OF-WeP7, 22 DeOrnellas, S.P.: DI+EL+MS-ThA8, 41 DeSisto, W.J.: TF+EL-WeA9, 34 Desjardins, P.: SC+EL+SS-MoA2, 3; SC+EL+SS-WeA6. 32 D'Evelyn, M.P.: SC+EL+SS-ThM9, 40 Dewitte, H.: DI+EL+MS-ThM9, 36 Dille, B.: SC+EL+SS-WeA9, 32 Dimitrova, V.I.: SC+EL+SS-WeP18, 26 Ditizio, R.A.: DI+EL+MS-ThA8, 41 Doak, R.B.: SC+SS+EL-ThA4, 42 Dong, J.W.: MI+EL-WeA3, 30; MI+EL-WeM1, 19; MI+EL-WeM2, 19 Donnelly, J.: DI+EL+MS-WeA3, 29 Doren, D.J.: SC+EL+OF-TuA1, 13; SC+EL+OF-TuA10, 14; SC+EL+SS-MoA9, 4 Dötz, F.: OF+EL+SS-ThM1, 37 Dowben, P.A.: OF+EL+SS-ThM11, 38 Dowell, N.: BI+EL-TuA7, 11 Ducharme, S.: OF+EL+SS-ThM11, 38 Duda, L.C.: SS2+EL-MoA1, 4 Dulcey, C.S.: OF+EL+SS-ThM9, 38 Dunham, G.C.: DI+EL+MS-WeM1, 18 Dupuis, R.D.: SC+EL+SS-TuM3, 7 Dürr, M.: SC+EL+SS-WeP7, 25 Durrant, S.F.: EL-TuP8, 16; EL-TuP9, 16 Dutton, G.: OF+EL+SS-WeM4, 21 Dziobkowski, C.: SC+EL+SS-WeP15, 26 — E — Eddy, Jr., C.R.: SC+EL-FrM3, 44 Ekerdt, J.G.: SC+EL+SS-ThM2, 39 Ellison, M.D.: SC+EL+SS-WeP1, 23 El-Masry, N.A.: MI+EL-WeA4, 31 Emanetoglu, N.W.: SC+EL+SS-TuM9, 8 Eng, Jr., J.: DI+EL+MS-ThM5, 35; DI+EL+MS-ThM7, 36 Enomoto, A.: EL+NS-TuA8, 13 Evans, C.E.: SS2+NS+BI+EL-TuM8, 10 — F — Faik, A.: SC+EL+SS-WeP24, 27 Farr, D.: SS2+EL-MoA5, 5 Farr, J.D.: SS2+EL-MoA6, 5

Author Index

Farzad, F.: OF+EL+SS-ThM9, 38 Fauster, Th.: SS2+EL-MoA7, 5 Fedorov, A.: SS2+EL-MoA1, 4 Feng, J.W.: SC+EL+SS-WeP9, 25 Fernandez, V.: DI+EL+MS-ThM11, 36 Figus, M.T.: MI+EL-WeM1, 19 Finnie, P.: SC+EL+SS-WeA10, 33 Fischer, D.A.: SS2+NS+BI+EL-TuM8, 10 Fitzgerald, D.R.: SC+EL+OF-TuA10, 14 Flagan, R.C.: EL+NS-TuA7, 12 Flaherty, F.: OF-WeP11, 23 Fleming, J.: EL+NS-TuM11, 7 Flores, L.D.: SC1+EL+SS-MoM5, 1 Forsythe, E.F.: EL+NS-TuM6, 6 Fouquet, P.: TF+EL-WeA1, 33 Franciosi, A.: EL-TuP4, 15 Frey, S.: SS2+NS+BI+EL-TuM9, 10 Fridkin, V.M.: OF+EL+SS-ThM11, 38 Frisbie, C.D.: OF+EL+SS-WeM3, 21; OF+EL+SS-WeM6. 21 Fritz, T.: OF+EL+SS-ThM7, 38; OF-WeP3, 22 Fryxell, G.E.: DI+EL+MS-WeM1, 18 Fu, Q.: SC+EL+OF-TuA5, 13; SC+EL+SS-ThM5, 39; SC+EL+SS-TuM5, 8 Fujikawa, Y.: SC+EL+SS-MoA4, 3 Fujimori, M.: SC+EL+SS-MoA3, 3 Fujita, D.: OF-WeP7, 22 Fukarek, W.: TF+EL-WeA5, 34 Fukushima, H.: SS2+NS+BI+EL-TuM10, 10 Fukutani, K.: SC+EL+SS-ThM11, 40 — G — Gall, D.: SC+EL+SS-WeA6, 32; SC+SS+EL-ThA8. 43 Gan, S.: DI+EL+MS-WeA9, 30 Gao, W.: OF-WeP2, 22 Gao, Y.: DI+EL+MS-ThA5, 41; EL+NS-TuM6, 6; OF-WeP10, 23; OF-WeP5, 22; OF-WeP6, 22 Garfunkel, E.: DI+EL+MS-ThM1, 35 Gaspar, D.J.: DI+EL+MS-WeA9, 30 George, M.A.: SC+EL+SS-WeP20, 27 Gerbi, J.E.: SC+EL+SS-WeP26, 28 Gibson, J.M.: SC+EL+SS-WeA4, 32; SC+EL+SS-WeP26, 28 Gila, B.P.: SC+EL-FrM11, 45 Girolami, G.S.: EL-TuP2, 15 Gland, J.L.: SS2+NS+BI+EL-TuM8, 10 Glasmastar, K.: BI+EL-TuA3, 11 Glass, G.: SC+EL+SS-MoA2, 3 Gleason, K.K.: DI+EL+MS-WeM5, 18; TF+EL-WeA2, 33 Godlevsky, V.: MI+EL-WeM2, 19 Goedde, D.M.: EL-TuP2, 15 Goghero, D.: DI+EL+MS-ThM11, 36 Gomez, W.: EL-TuP7, 16 Gorla, C.R.: SC+EL+SS-TuM9, 8 Goto, T.: DI+EL+MS-WeA7, 29 Goullet, A.: DI+EL+MS-ThM11, 36 Grandidier, B.: OF+EL+SS-ThM5, 37 Granier, A.: DI+EL+MS-ThM11, 36 Green, M.L.: DI+EL+MS-ThM5, 35 Greenbaum, E.: EL+NS-TuM5, 6 Greenblatt, M.: SS2+EL-MoA1, 4 Greene, J.E.: SC+EL+SS-MoA2, 3; SC+EL+SS-WeA6, 32; SC+SS+EL-ThA8, 43 Greenlief, C.M.: SC+EL+OF-TuA6, 14 Grosse, F.: SC+EL+SS-TuM1, 7 Gruetter, P.: EL+NS-TuA10, 13 Grunze, M.: SS2+NS+BI+EL-TuM2, 9; SS2+NS+BI+EL-TuM9, 10 Guerin, D.: SC+EL+SS-WeA7, 32 Guerra, E.M.: EL-TuP12, 16 Guillorn, M.A.: EL+NS-TuM5, 6 Guisinger, N.P.: EL+NS-TuM8, 6 Gyure, M.: SC+EL+SS-TuM1, 7

Author Index

— Н — Haji, S.: SC+EL+SS-WeP25, 27 Hale, M.: SC+EL+SS-WeP21, 27 Hamers, R.J.: SC+EL+OF-TuA7, 14; SC+EL+OF-TuA9, 14; SC+EL+SS-ThM9, 40; SC+EL+SS-WeP1, 23 Han, J.: SC+EL-FrM1, 44; SC+EL-FrM10, 45 Han, M.: SC+EL+SS-TuM7, 8 Hanbicki, A.T.: MI+EL-WeA6, 31; MI+EL-WeM6, 20 Hara, M.: SS2+NS+BI+EL-TuM10, 10 Haraichi, S.: SC+EL+SS-MoA10, 4 Harasek, S.: DI+EL+MS-WeM8, 19 Harris, K.K.: SC+EL-FrM11, 45 Hasan, M.-A.: SC+EL+SS-WeP24, 27 Hase, M.: SC+EL+SS-WeP12, 25 Hashizume, T.: SC+EL+SS-MoA3, 3 Hasko, D.G.: EL+NS-TuA1, 12 Hefty, R.C.: SC+EL+SS-WeP6, 24 Heike, S.: SC+EL+SS-MoA3, 3 Heinz, T.F.: SC+EL+SS-WeP7, 25 Heister, K.: SS2+NS+BI+EL-TuM2, 9; SS2+NS+BI+EL-TuM9, 10 Henry, R.L.: SC+SS+EL-ThA1, 42 Hensley, D.K.: SC+EL+SS-WeP20, 27 Herne, T.M.: SS2+NS+BI+EL-TuM5, 9 Hersam, M.C.: EL+NS-TuM8, 6 Hess, J.S.: SC+EL+SS-MoA9, 4 Hess, K.: SC+EL+SS-ThM10, 40; SC+EL+SS-WeP3. 24 Heyns, M.M.: DI+EL+MS-ThM9, 36 Hickman, J.J.: BI+EL-TuA8, 11 Hicks, R.F.: SC+EL+OF-TuA5, 13; SC+EL+SS-ThM5, 39; SC+EL+SS-TuM5, 8 Hill, I.G.: OF+EL+SS-ThM2, 37 Hirayama, Y.: SC+EL+SS-TuM2, 7 Hobson, W.S.: SC+EL-FrM1, 44 Höfer, U.: SC+EL+SS-ThM3, 39; SC+EL+SS-WeP7, 25 Holmes, Jr., A.L.: SC+EL-FrM4, 44 Holt, J.R.: SC+EL+SS-WeP6, 24 Homma, Y .: SC+EL+SS-WeA10, 33 Honda, M.: SC+EL+SS-WeP15, 26 Hori, M.: DI+EL+MS-WeA7, 29 Horino, Y.: SC+EL+SS-WeP14, 26 Hovis, J.: SC+EL+SS-ThM9, 40 Hu, C.: SC+EL+SS-WeP23, 27 Hu, Z.: SC+EL+SS-WeP7, 25 Hul'ko, O.: EL+NS-TuM7, 6 Hwang, C.: SC+EL+SS-MoA8, 4 Hwang, G.S.: SC+EL+SS-WeP22, 27 Hwang, H.: DI+EL+MS-ThM6, 36 Hwang, H.-J.: SC+EL+SS-WeP27, 28 -1 lannotta, S.: OF+EL+SS-ThM6, 37 Ichimura, S.: DI+EL+MS-ThM2, 35; SC1+EL+SS-MoM7, 1 Ila, D.: SC+EL+SS-WeP20, 27 Isaacson, M.S.: BI+EL-TuA7, 11 Ishida, T.: SS2+NS+BI+EL-TuM4, 9 Ishioka, K.: SC+EL+SS-WeP12, 25 Itoh, H.: SC1+EL+SS-MoM7, 1 -1-Jackson, G.J.: DI+EL+MS-ThM4, 35 Jackson, T.N.: EL+NS-TuM6, 6 Jadwisienczak, W.M.: SC+SS+EL-ThA9, 43 James, C.D.: BI+EL-TuA7, 11 Jang, H.S.: DI+EL+MS-ThM6, 36 Jang, Y.C.: EL-TuP15, 17; EL-TuP3, 15 Jeng, D.G.-K.: SC+EL-FrM2, 44 Jeon, H.: SC+EL+SS-WeP19, 26 Jerde, L.G.: DI+EL+MS-ThA8, 41 Jiang, J.C.: DI+EL+MS-ThA7, 41 Jin, C.: DI+EL+MS-WeM1, 18 Jingguo, Z.: EL-TuP8, 16

Jintsugawa, O.: SC1+EL+SS-MoM4, 1 Jo, H.M.: DI+EL+MS-ThM6, 36 Jo, S.K.: SC+EL+SS-ThM2, 39 Johansson, L.: SS2+NS+BI+EL-TuM2, 9 Johnson, P.D.: SS2+EL-MoA1, 4 Johnson, W.: SC+EL-FrM11, 45 Jonker, B.T.: MI+EL-WeA1, 30; MI+EL-WeA6, 31; MI+EL-WeM3, 19; MI+EL-WeM6, 20 Jordan, D.C.: SC+SS+EL-ThA4, 42 Jung, D.-Y.: EL-TuP15, 17 Jung, I.N.: SC+EL+SS-WeP16, 26 Junno, T.: EL+NS-TuA5, 12 - K -Kafafi, Z.H.: OF+EL+SS-ThM2, 37 Kagadei, V.A.: SC+EL+SS-WeP4, 24 Kahn, A.: OF+EL+SS-ThM3, 37; OF+EL+SS-WeM5, 21; OF-WeP2, 22; SS2+NS+BI+EL-TuM3.9 Kajiyama, H.: SC+EL+SS-MoA3, 3 Kalinin, S.V.: DI+EL+MS-ThA4, 41 Kamachi, H.: BI+EL-TuA10, 12 Kang, E.-S.: SC+EL+SS-WeP27, 28 Kang, H.: SC+EL+SS-WeP19, 26 Kang, J.H.: SC+EL+SS-ThM2, 39 Kang, J.-W.: SC+EL+SS-WeP27, 28 Kanisawa, K.: SC+EL+SS-TuM2, 7 Karabutov, A.: SC+EL-FrM6, 44 Karthikeyan, S.: SC+EL+SS-WeA8, 32 Kasemo, B.: BI+EL-TuA3, 11 Kawashima, Y.: SC+EL+SS-ThM11, 40 Keister, J.W.: DI+EL+MS-ThM3, 35; DI+EL+MS-ThM4, 35; DI+EL+MS-ThM8, 36 Kelly, K.F.: SC+EL+SS-MoA4, 3 Kelly, M.J.: DI+EL+MS-WeA10, 30 Kentsch, C.: SS2+EL-MoA7, 5 Kevan, S.D.: SS2+EL-MoA3, 4 Khakifirooz, A.: SC+EL+SS-WeP25, 27 Khan, K.A.: SC+EL+SS-TuM11, 8 Kido, J.: OF+EL+SS-WeM7, 21 Kim, C.-I.: EL-TuP11, 16; EL-TuP13, 16; EL-TuP14.17 Kim, D.: OF+EL+SS-ThM10, 38 Kim, D.W.: SC+EL+SS-WeP17, 26 Kim, E.: SC+EL-FrM6, 44; SC+SS+EL-ThA3, 42 Kim, H.: SC+EL+SS-MoA2, 3 Kim, H.J.: DI+EL+MS-ThA3, 41 Kim, H.K.: DI+EL+MS-ThM6, 36 Kim, H.S.: SC+EL+SS-WeP17, 26 Kim, H.-Y.: DI+EL+MS-WeA5, 29 Kim, K.J.: EL-TuP15, 17 Kim, K.S.: EL-TuP15, 17; EL-TuP3, 15 Kim, N.-H.: EL-TuP11, 16 Kim, S.: DI+EL+MS-ThA3, 41 Kim, S.H.: SC+EL+SS-ThM2, 39 Kim, T.-H.: EL-TuP11, 16; EL-TuP14, 17 Kim, Y.C.: EL-TuP13, 16; SC+EL+SS-WeP19, 26 Kim, Y.K.: SC+EL+SS-WeP3, 24 Kim, Y.T.: EL-TuP13, 16 Kim, Y.W.: SC+EL+SS-WeP3, 24 Kim, Yunsoo: SC+EL+SS-WeP16, 26 Kimura, Y.: SC+EL+SS-MoA1, 3 Kinomura, A.: SC+EL+SS-WeP14, 26 Kintzel, Jr., E.J.: OF-WeP11, 23 Kioseoglou, G.: MI+EL-WeM3, 19 Kitajima, M.: SC+EL+SS-WeP12, 25 Kitazawa, K.: SC+EL+SS-MoA3, 3 Knoch, J.: EL+NS-TuA6, 12 Ko, D.-H.: DI+EL+MS-WeA5, 29 Koleske, D.D.: SC+SS+EL-ThA1, 42 Komiyama, M.: OF-WeP9, 23 Kordesch, M.E.: SC+EL+SS-WeP18, 26; SC+SS+EL-ThA10, 43 Krenzer, B.: TF+EL-WeA4, 33 Krishnamoorthy, V.: SC+EL-FrM11, 45

Kruse, P.: SC+EL+SS-TuM6, 8; SC+EL+SS-WeP21.27 Krzeminski, C.: OF+EL+SS-ThM5, 37 Kummel, A.C.: SC+EL+SS-TuM6, 8; SC+EL+SS-WeP21, 27 Kuo, C.S.: EL+NS-TuM6, 6 Kuo, T.-N.: SC+EL-FrM2, 44 Kuo, Y.: DI+EL+MS-WeA3, 29 Kurokawa, A.: DI+EL+MS-ThM2, 35; SC1+EL+SS-MoM7, 1 Kurokawa, S.: EL+NS-TuA8, 13 Kutschera, M.: SS2+EL-MoA7, 5 Kwon, K.-H.: EL-TuP14, 17 Kwon, O.: OF+EL+SS-ThM10, 38 -1-LaFave Jr., T.: SC+EL+SS-WeP24, 27 Lahav, M.: OF-WeP4, 22 Lakshminarayana, N.: SC+EL+SS-WeP24, 27 Langell, M.A.: SC+EL+SS-WeP2, 24 Langfischer, H.: DI+EL+MS-WeM8, 19 Laracuente, A.: SC+EL+SS-ThM1, 38 Lashley, J.: SS2+EL-MoA5, 5 Law, D.C.: SC+EL+OF-TuA5, 13 Le. Q.T.: EL+NS-TuM6. 6 Leburton, J.-P.: SC+EL+SS-ThM10, 40 Lee, A.: SC+EL+SS-ThM6, 39 Lee, C.: EL-TuP5, 15 Lee, C.C.: MI+EL-WeA5, 31 Lee, C.M.: SC+EL-FrM10, 45 Lee, D.C.: OF-WeP1, 22 Lee, G.: OF+EL+SS-ThM10, 38; SC+EL+SS-MoA8. 4 Lee, H.: SC+EL+SS-MoA8, 4 Lee, H.J.: DI+EL+MS-ThM6. 36 Lee, H.-J.: DI+EL+MS-WeA5, 29 Lee, H.-J.: SC+EL-FrM2, 44 Lee, I.: EL+NS-TuM5, 6 Lee, J.: EL+NS-TuM5, 6; SC+EL+SS-ThM10, 40; SC+EL+SS-ThM2, 39; SC+EL+SS-ThM6, 39; SC+EL+SS-WeP3, 24 LEE, J.H.: DI+EL+MS-WeM7, 19 Lee, J.W.: SC+EL-FrM1, 44; SC+SS+EL-ThA7, 42 Lee, K.N.: SC+EL-FrM11, 45 Lee, K.P.: SC+EL+SS-WeP13, 26; SC+EL-FrM1, 44; SC+EL-FrM10, 45 Lee, K.-W.: SC+EL+SS-WeP16, 26 Lee, M.-H.: TF+EL-WeA3, 33 Lee, N.-E.: EL-TuP15, 17; EL-TuP3, 15 Lee, R.: SS2+NS+BI+EL-TuM3, 9 Lee, S.-B.: SC+EL+SS-WeP16, 26 Lee, S.W.: OF-WeP1, 22 Lee, T.R.: SS2+NS+BI+EL-TuM10, 10 Lee, Y.: SC+EL+SS-ThM6, 39 Lee, Y.M.: DI+EL+MS-ThM3, 35 Leerungnawarat, P.: SC+EL+SS-WeP13, 26 Leggett, G.J.: BI+EL-TuA5, 11 Leo, K.: OF+EL+SS-ThM7, 38; OF-WeP3, 22 Letourneur, K.Y.: TF+EL-WeA8, 34 Leung, M.: EL-TuP5, 15 Li, C.H.: SC+EL+OF-TuA5, 13; SC+EL+SS-ThM5, 39; SC+EL+SS-TuM5, 8 Li, L.: SC+EL+SS-ThM5, 39; SC+EL+SS-TuM5, 8 Li. W.: SC+EL+SS-WeA7. 32 Li, X.: DI+EL+MS-WeM1, 18 Liang, S.: SC+EL+SS-TuM9, 8 Liang, Y.: DI+EL+MS-WeA9, 30 Lidberg, U.: BI+EL-TuA3, 11 LIM, C.R.: DI+EL+MS-WeM7, 19 Lin, J.H.: DI+EL+MS-WeM3, 18 Lin. M.: EL-TuP6. 15 Lin, Y.: DI+EL+MS-WeA6, 29 Lin, Y.-S.: EL-TuP1, 15 Liu, C.P.: SC+EL+SS-WeA4, 32 Liu, F.: MI+EL-WeM8, 20

Liu, H.: SC+EL+OF-TuA7, 14 Liu, J.: DI+EL+MS-WeM1, 18; SC+EL+OF-TuA7, 14; SC+EL+OF-TuA9, 14 Liu, L.: EL+NS-TuM8, 6 Liu, W.: EL-TuP6, 15 Liu, X.W.: DI+EL+MS-WeM3, 18 Liu, Z.: SC+EL+SS-ThM11, 40 Loh, W.B.: DI+EL+MS-WeM6, 18 Loong, S.Y.: DI+EL+MS-WeM4, 18; DI+EL+MS-WeM6, 18 Lopinski, G.P.: EL+NS-TuM7, 6 Loubnin, E.: SC+EL-FrM6, 44 Lozykowski, H.J.: SC+SS+EL-ThA9, 43 Lu, J.: MI+EL-WeA3, 30; MI+EL-WeM2, 19 Lu, Y.: SC+EL+SS-TuM9, 8 Lucovsky, G.: DI+EL+MS-ThM3, 35; DI+EL+MS-WeA4, 29; EL-TuP10, 16 Lugstein, A.: DI+EL+MS-WeM8, 19 Luo, L.: SC+EL+SS-WeP23, 27 Luo, Y.: SC+EL+SS-TuM7, 8 Lyding, J.W.: EL+NS-TuM8, 6; SC+EL+SS-ThM10, 40; SC+EL+SS-WeP3, 24 — M — Mabboux, P.-Y.: DI+EL+MS-WeM5, 18 Madey, T.E.: DI+EL+MS-ThM4, 35 Maeng, J.Y.: SC+EL+SS-ThM2, 39 Maennig, B.: OF-WeP3, 22 Magno, R.: MI+EL-WeA6, 31 Makinen, A.J.: OF+EL+SS-ThM2, 37 Mandal, K.C.: SC+EL+SS-WeA9, 32 Mankey, G.J.: MI+EL-WeM8, 20 Marks, S.: DI+EL+MS-ThA8, 41 Marsh, A.L.: SS2+NS+BI+EL-TuM8, 10 Martel, R.: EL+NS-TuA6, 12 Martinez, A.: EL-TuP7, 16 Masaitis, R.L.: DI+EL+MS-ThM5, 35 Mason, M.G.: OF-WeP5, 22; OF-WeP6, 22 Matsumoto, M.: SC+EL+SS-ThM11, 40 Matsushita, M.: BI+EL-TuA10, 12 Matsuura, S.: SC+EL+SS-MoA3, 3 Matsuura, T.: SC1+EL+SS-MoM1, 1; SC1+EL+SS-MoM4, 1 Mattson, J.E.: MI+EL-WeA6, 31; MI+EL-WeM6, 20 McBreen, P.H.: OF-WeP12, 23 McCarroll, W.: SS2+EL-MoA1, 4 McCarty, P.: SC+EL+SS-WeP20, 27 McCready, D.E.: DI+EL+MS-WeA9, 30 McKernan, S.: MI+EL-WeM1, 19 McLean, J.G.: SC+EL+SS-TuM6, 8 Medvedev, V.K.: DI+EL+MS-WeA8, 30 Meng, S.: SC+EL+SS-MoA7, 4 Mensing, T.: SS2+EL-MoA4, 5 Messier, R.: TF+EL-WeA7, 34 Meyer, F.: DI+EL+MS-ThM11, 36 Meyer, J.A.: DI+EL+MS-ThA8, 41 Milani, P.: OF+EL+SS-ThM6, 37 Miller, C.C.: SS2+NS+BI+EL-TuM5, 9 Min, B.J.: EL-TuP13, 16 Miranda, F.: DI+EL+MS-ThA7, 41 Miyamoto, M.: DI+EL+MS-ThM2, 35 Mizutani, W.: SS2+NS+BI+EL-TuM4, 9 Moffatt, D.J.: EL+NS-TuM7, 6 Mohajerzadeh, S.S.: SC+EL+SS-WeP25, 27 Mooij, E.L.: EL+NS-TuA3, 12 Moon, D.W.: DI+EL+MS-ThM6, 36 Morikawa, Y.: DI+EL+MS-ThM2, 35 Moustakas, T.D.: SC+EL-FrM3, 44 Mrksich, M.: BI+EL-TuA1, 11 Mui, C.: SC+EL+OF-TuA8, 14; SC+EL+SS-ThM7, 39 Müllen, K.: OF+EL+SS-ThM1, 37 Müller, T.A.R.: EL-TuP4, 15 Muntele, C.I.: SC+EL+SS-WeP20, 27 Muntele, I.: SC+EL+SS-WeP20, 27

Murota, J.: SC1+EL+SS-MoM1, 1; SC1+EL+SS-MoM4, 1 Musgrave, C.B.: SC+EL+OF-TuA8, 14; SC+EL+SS-ThM7, 39; SC1+EL+SS-MoM3, 1 Muthukumar, S.: SC+EL+SS-TuM9, 8 -N-Naaman, R.: OF-WeP4, 22; OF-WeP8, 23 Nagasawa, J.: SS2+NS+BI+EL-TuM7, 10 Nakamura, K.: SC1+EL+SS-MoM7, 1 Nakayama, K.S.: SC+EL+SS-MoA4, 3 Nam, S.-W.: DI+EL+MS-WeA5, 29 Nathan, M.I.: EL-TuP4, 15 Navarro-Contreras, H.: SC+EL+SS-WeP10, 25 Nefedtsev, E.V.: SC+EL+SS-WeP4, 24 Nejoh, H.: OF-WeP7, 22 Nelson, S.F.: EL+NS-TuM6, 6 Ng, H.M.: SC+EL-FrM3, 44 Niehus, H.: TF+EL-WeA4, 33 Nishida, J.: BI+EL-TuA10, 12 Nishiguchi, T.: DI+EL+MS-ThM2, 35 Nishikawa, K.: BI+EL-TuA10, 12 Nishikawa, T.: BI+EL-TuA10, 12 Nishimura, S.-I.: BI+EL-TuA10, 12 Niu, D.: DI+EL+MS-WeA10, 30 Nivens, D.: EL+NS-TuM11, 7 Niwano, M.: SC+EL+SS-MoA1, 3 Noda, T.: OF+EL+SS-ThM2, 37 Nonaka, H.: DI+EL+MS-ThM2, 35 Nosho, B.Z.: SC+EL+SS-TuM10, 8 Nys, J.P.: OF+EL+SS-ThM5, 37 -0-Oh, C.-S.: EL-TuP14, 17 Oh. S.-H.: DI+EL+MS-WeA5. 29 Ohgi, T.: OF-WeP7, 22 Ohno, H.: MI+EL-WeM4, 20 Ohta, H.: DI+EL+MS-WeA7, 29 Ohuchi, F.S.: SC+EL+SS-MoA7, 4; TF+EL-WeA3. 33 Olmstead, M.A.: SC+EL+SS-MoA7, 4 Olson, K.A.: DI+EL+MS-ThA8, 41 Onogi, T.: SC+EL+SS-MoA3, 3 Ookubo, H.: BI+EL-TuA10, 12 Ookura, R.: BI+EL-TuA10, 12 Opila, R.L.: DI+EL+MS-ThM5, 35; DI+EL+MS-ThM7, 36 Osgood, Jr., R.M.: SC+EL+SS-TuM11, 8 Osgood, R.M.: SC+EL+SS-TuM7, 8 Ostraat, M.: EL+NS-TuA7, 12 Oudghiri-Hassani, H.: OF-WeP12, 23 Overberg, M.E.: SC+EL-FrM7, 44 Owen, J.H.G.: SC+EL+SS-TuM1, 7 — P — Paek, S.W.: DI+EL+MS-WeM7, 19 Palmstrom, C.J.: EL-TuP4, 15; MI+EL-WeA3, 30; MI+EL-WeM1, 19; MI+EL-WeM2, 19 Palto, S.P.: OF+EL+SS-ThM11, 38 Park, C.-G.: DI+EL+MS-WeA5, 29 Park, C.Y.: EL-TuP15, 17 Park, G.B.: OF-WeP1, 22 Park, S.H.: OF-WeP1, 22 Park, Y.: OF+EL+SS-ThM10, 38; SC+EL+SS-MoA8.4 Park, Y.D.: MI+EL-WeA6, 31; MI+EL-WeM3, 19: MI+EL-WeM6. 20 Parkinson, B.A.: OF+EL+SS-ThM8, 38 Parsons, G.N.: DI+EL+MS-WeA10, 30 Patitsas, S.N.: EL+NS-TuM7, 6 Patounakis, G.: SC+EL+SS-TuM9, 8 Pearton, S.J.: SC+EL+SS-WeP13, 26; SC+EL-FrM1, 44; SC+EL-FrM10, 45; SC+EL-FrM11, 45; SC+EL-FrM7, 44 Pehrsson, P.E.: OF+EL+SS-ThM9, 38 Perovic, D.D.: SC+EL+SS-WeA3, 31 Peterlevitz, A.C.: EL-TuP8, 16; EL-TuP9, 16 Petroff, P: MI+EL-WeM7, 20

Petronis, S.: BI+EL-TuA3, 11 Petrou, A.: MI+EL-WeM3, 19 Petrov, I.: SC+EL+SS-WeA6, 32; SC+SS+EL-ThA8, 43 Petukhov, A.G.: MI+EL-WeA7, 31 Petukhova, N.: OF+EL+SS-ThM11, 38 Pfeiffer, M.: OF-WeP3, 22 Pflaum, J.: SS2+NS+BI+EL-TuM3, 9 Podest@aa a@, A.: OF+EL+SS-ThM6, 37 Poelsema, B.: SC+EL+SS-WeA5, 32 Poirier, G.E.: SS2+NS+BI+EL-TuM5, 9 Poker, D.B.: SC+EL+SS-WeP20, 27 Porath, D.: EL+NS-TuM9, 7 Prayongpan, P.: SC+EL+OF-TuA6, 14 Presser, N.: EL-TuP5, 15 Proehl, H.: OF+EL+SS-ThM7, 38 Proskurovsky, D.I.: SC+EL+SS-WeP4, 24 Pryadkin, S.L.: EL+NS-TuA9, 13 Pugmire, D.L.: SC+EL+SS-WeP2, 24 Puntambekar, K.: OF+EL+SS-WeM3, 21 - Q -Quan, Y.C.: EL-TuP15, 17 Queeney, K.T.: DI+EL+MS-ThM7, 36; SC1+EL+SS-MoM2, 1; SC1+EL+SS-MoM8, 2 — R — Rabani, E.: OF-WeP4, 22 Raghavachari, K.: SC1+EL+SS-MoM2, 1 Ramachandran, R.: SC+EL+SS-WeP15, 26 Ramesh, R.: DI+EL+MS-ThA1, 41 Ratsch, C.: SC+EL+SS-TuM1, 7 Rauh, R.D.: SC+EL+SS-WeA9, 32 Raviswaran, A.: SC+EL+SS-WeA4, 32 Rayner, B.: DI+EL+MS-WeA4, 29 Reed. M.L.: MI+EL-WeA4. 31 Ren, F.: SC+EL+SS-WeP13, 26; SC+EL-FrM1, 44; SC+EL-FrM10, 45; SC+EL-FrM11, 45 Richardson, H.H.: SC+EL+SS-WeP18, 26 Richter-Dahlfors, A.: BI+EL-TuA3, 11 Ripp, S.: EL+NS-TuM11, 7 Rodriguez, A.G.: SC+EL+SS-WeP10, 25 Rodriguez, M.: EL-TuP7, 16 Rogers, Jr., J.W.: DI+EL+MS-WeA8, 30 Roh, K.: EL-TuP3, 15 Roh, Y.: EL-TuP3, 15 Röhr, E.: DI+EL+MS-ThM9, 36 Roncali, J.: OF+EL+SS-ThM5, 37 Ronchin, S.: OF+EL+SS-ThM6, 37 Rong, H.: SS2+NS+BI+EL-TuM2, 9 Rosamilia, J.M.: DI+EL+MS-ThM5, 35 Rosenbaum, E.: SC+EL+SS-ThM10, 40 Ross, R.S.: SC+EL+SS-TuM1, 7 Rotenberg, E.: SS2+EL-MoA3, 4; SS2+EL-MoA5, 5 Rowe, J.E.: DI+EL+MS-ThM3, 35; DI+EL+MS-ThM4, 35; DI+EL+MS-ThM8, 36 Ruda, H.E.: SC+EL+SS-WeA3, 31 Russell, Jr., J.N.: SC+EL+SS-ThM9, 40 Ryan, P.: SC+EL+SS-WeP11, 25 — S — Sadowski, J.T.: SC+EL+SS-MoA4, 3 Safron, S.A.: OF-WeP11, 23 Sakai, A.: EL+NS-TuA8, 13 Sakuraba, M.: SC1+EL+SS-MoM1, 1; SC1+EL+SS-MoM4.1 Sakurai, T.: SC+EL+SS-MoA4, 3 Samokhvalov, A.: OF-WeP4, 22; OF-WeP8, 23 Samuelson, L.: EL+NS-TuA5, 12 Sapjeta, J.: DI+EL+MS-ThM5, 35 Sasaki, F.: SC+EL+SS-MoA10, 4 Sasaki, J.: EL+NS-TuA8, 13 Sawaguchi, T.: SS2+NS+BI+EL-TuM11, 10 Sawin, H.H.: TF+EL-WeA2, 33 Sayler, G.S.: EL+NS-TuM11, 7 Schram, D.C.: TF+EL-WeA10, 34

Schroeder, B.R.: SC+EL+SS-MoA7, 4 Schulze, R.K.: SS2+EL-MoA5, 5; SS2+EL-MoA6, 5 Schwartz, J.: OF+EL+SS-WeM5, 21 Schwartz, M.P.: SC+EL+OF-TuA9, 14; SC+EL+SS-WeP1, 23 Scoles, G.: SS2+NS+BI+EL-TuM3, 9 See, K.H.: DI+EL+MS-WeM4, 18 Sekine, R.: SS2+NS+BI+EL-TuM11, 10 Sellam, F.: OF+EL+SS-ThM7, 38 Seo, H.: SC+EL+SS-WeP19, 26 Seo, J.M.: SS2+EL-MoA8, 5 Seyama, A.: SC+EL+SS-MoA1, 3 Shah, S.I.: SC+EL+SS-WeA7, 32 Shain, W.: BI+EL-TuA7, 11 Shanabrook, B.V.: SC+EL+SS-TuM10, 8 Shashidar, R.: OF+EL+SS-ThM9, 38 Shen, C.: OF+EL+SS-WeM5, 21 Shen, J.: DI+EL+MS-ThA7, 41 Sherchenkov, A.A.: SC+EL+SS-WeP5, 24 Shigekawa, H.: OF-WeP9, 23 Shih, H.C.: DI+EL+MS-WeM3, 18 Shim, K.-H.: EL-TuP3, 15 Shimomura, M.: BI+EL-TuA10, 12 Shin, C.B.: SC+EL+SS-WeP22, 27 Shin, D.O.: EL-TuP3, 15 Shinohara, M.: SC+EL+SS-MoA1, 3 Shirota, Y.: OF+EL+SS-ThM2, 37 Shuh, D.: SS2+EL-MoA5, 5 Shumay, I.L.: SS2+EL-MoA7, 5 Siaj, M.: OF-WeP12, 23 Silverman, P.: DI+EL+MS-ThM5, 35 Simpson, M.L.: EL+NS-TuM11, 7; EL+NS-TuM5, 6 Singh, R.: SC+EL-FrM3, 44 Siu, W.-K.: SS2+EL-MoA4, 5 Skofronick, J.G.: OF-WeP11, 23 Smilgies, D.-M.: OF-WeP11, 23 Smith, A.R.: SC+SS+EL-ThA9, 43 Smith, D.J.: SC+SS+EL-ThA4, 42 Smith, K.E.: SC+EL+SS-WeP11, 25; SS2+EL-MoA1. 4 Smith, K.V.: SC+EL-FrM8, 45 Soares, J.A.N.T.: SC+EL+SS-MoA2, 3 Soh, H.: SC+EL+SS-WeP19, 26 Solomon, P.: EL+NS-TuA6, 12 Sorokin, A.V.: OF+EL+SS-ThM11, 38 Sorsch, T.: DI+EL+MS-ThM5, 35 Spanos, G.: MI+EL-WeM6, 20 Spence, A.J.: BI+EL-TuA7, 11 Stadelmaier, H.H.: MI+EL-WeA4, 31 Stawasz, M.E.: OF+EL+SS-ThM8, 38 Stenzel, W.: TF+EL-WeA4, 33 Stievenard, D.: OF+EL+SS-ThM5, 37 Stripe, D.S.: SC+EL+OF-TuA6, 14 Stupian, G.: EL-TuP5, 15 Su, J.: MI+EL-WeA5, 31 Subrahmanyam, A.: DI+EL+MS-ThM10, 36; SC+EL+SS-WeA8, 32 Suh, K.P.: SC+EL+SS-WeP3, 24 Sumaoka, J.: OF-WeP9, 23 Sung, J.H.: EL-TuP2, 15 Sung, Y.J.: SC+EL+SS-WeP17, 26 Sutherland, D.S.: BI+EL-TuA3, 11 Suwa, Y.: SC+EL+SS-MoA3, 3 Suzuki, A.: SS2+NS+BI+EL-TuM10, 10 Suzuki, I.: OF-WeP9, 23 — т – Takakuwa, Y.: SC+EL+SS-ThM8, 39 Takeda, N.: OF+EL+SS-ThM8, 38 Tamada, K.: SS2+NS+BI+EL-TuM10, 10; SS2+NS+BI+EL-TuM7, 10 Tang, C.W.: OF-WeP5, 22; OF-WeP6, 22 Tanner. M.: EL+NS-TuA6. 12 Tarlov, M.J.: SS2+NS+BI+EL-TuM5, 9

Tate, M.R.: SC+EL+SS-WeP6, 24 Teh, Y.W.: DI+EL+MS-WeM4, 18; DI+EL+MS-WeM6, 18 Tempez, A.: SC+EL-FrM6, 44; SC+SS+EL-ThA3, 42 Teraoka, Y.: SC+EL+SS-WeP8, 25 Terfort, A.: SS2+NS+BI+EL-TuM1, 9 Terry, J.: SS2+EL-MoA5, 5 Tewg, J.: DI+EL+MS-WeA3, 29 Therrien, R.: DI+EL+MS-WeA4, 29 Thomas, S.: EL+NS-TuA6, 12 Tiberio, R.: EL+NS-TuM5, 6 Toan, Q.T.: OF-WeP10, 23 Tobin, J.G.: SS2+EL-MoA5, 5 Toccoli, T.: OF+EL+SS-ThM6, 37 Todo, S.: BI+EL-TuA10, 12 Toerker, M.: OF+EL+SS-ThM7, 38 Tokumoto, H.: SS2+NS+BI+EL-TuM4, 9 Treacy, M.M.J.: SC+EL+SS-WeP26, 28 Trelenberg, T.W.: OF-WeP11, 23 Tsai, C.S.: MI+EL-WeA5, 31 Tsong, I.S.T.: SC+SS+EL-ThA4, 42 Tsubouchi, N.: SC+EL+SS-WeP14, 26 Tsung, L.: SC+EL+SS-WeP23, 27 Tuan, A.C.: DI+EL+MS-WeA8, 30 Turban, G.: DI+EL+MS-ThM11, 36 Turner, J.: BI+EL-TuA7, 11 Twigg, M.E.: SC+SS+EL-ThA1, 42 — U — Ugarov, M.: SC+EL-FrM6, 44 Ushida, K.: SC+EL+SS-WeP12, 25 - v van de Sanden, M.C.M.: TF+EL-WeA10, 34; TF+EL-WeA8. 34 van Hest, M.F.A.M: TF+EL-WeA10, 34 Van Keuls, F.W.: DI+EL+MS-ThA7, 41 Van Patten, P.G.: SC+EL+SS-WeP18, 26 Van Winkle, D.H.: OF-WeP11, 23 Vereecke, G.: DI+EL+MS-ThM9, 36 Vidal, M.A.: SC+EL+SS-WeP10, 25 Viernes, N.: EL+NS-TuM8, 6 von Keudell, A.: TF+EL-WeA8, 34 Voyles, P.M.: SC+EL+SS-WeP26, 28 -w-Wallace, R.M.: DI+EL+MS-WeA1, 29 Wang, G.T.: SC+EL+OF-TuA8, 14; SC+EL+SS-ThM9.40 Wang, H.: OF+EL+SS-WeM4, 21 Wang, J.F.T.: DI+EL+MS-ThM3, 35; DI+EL+MS-ThM4, 35 Wang, K.L.: EL+NS-TuA6, 12; SC+EL+SS-WeA1, 31 Wang, L.-Y.: EL-TuP16, 17 Wanzenboeck, H.D.: DI+EL+MS-WeM8, 19 Warren, W.L.: EL+NS-TuM1, 6 Watanabe, T.: SC1+EL+SS-MoM1, 1 Watkins, N.J.: EL+NS-TuM6, 6; OF-WeP10, 23 Webb, S.R.: BI+EL-TuA4, 11 Weinelt, M.: SS2+EL-MoA7, 5 Weir, B.E.: DI+EL+MS-ThM5, 35 Weiss. K.: OF+EL+SS-ThM1. 37 White, J.M.: SC+EL+SS-ThM2, 39 Whitman, L.J.: SC+EL+SS-ThM1, 38; SC+FL+SS-TuM10.8 Wickenden, A.E.: SC+SS+EL-ThA1, 42 Widjaja, Y.: SC1+EL+SS-MoM3, 1 Wiets, M.: SS2+EL-MoA7, 5 Wilde, M.: SC+EL+SS-ThM11, 40 Wilk, G.D.: DI+EL+MS-WeA1, 29 Willan, C.C.: SC+SS+EL-ThA5, 42 Willis, R.F.: SC+EL+SS-MoA5, 3 Wilson, A.: MI+EL-WeM6, 20 Witte, G.: TF+EL-WeA1, 33 Wlasenko, A.: EL+NS-TuA10. 13 Wold, D.J.: OF+EL+SS-WeM6, 21

Author Index

Wolkow, R.A.: EL+NS-TuM7, 6 Wöll, C.: OF+EL+SS-ThM1, 37; SS2+NS+BI+EL-TuM1, 9 Wong, K.S.: DI+EL+MS-WeM4, 18; DI+EL+MS-WeM6, 18 Wong, Y.C.: DI+EL+MS-WeM4, 18; DI+EL+MS-WeM6, 18 Woodbridge, C.M.: SC+EL+SS-WeP2, 24 Wu, W.: MI+EL-WeA5, 31 - x -Xie, J.Q.: MI+EL-WeA3, 30; MI+EL-WeM1, 19; MI+EL-WeM2, 19 Xu, B.: OF+EL+SS-ThM11, 38 Xu, H.: EL+NS-TuA5, 12; SC+EL+SS-ThM6, 39 Xue, J.: SS2+EL-MoA1, 4 -Y-Yamada, T.: SS2+NS+BI+EL-TuM11, 10 Yamaguchi, H.: SC+EL+SS-TuM2, 7 Yan, L.: EL+NS-TuM6, 6; OF-WeP5, 22; OF-WeP6, 22

Yan, X.: SC+EL+SS-ThM2, 39 Yarmoff, J.A.: SC+EL+SS-TuM11, 8 Yase, K.: OF-WeP9, 23 Yasuda, S.: OF-WeP9, 23 Yeh, J.-H.: SC+EL-FrM2, 44 Yeom, G.Y.: EL-TuP15, 17; SC+EL+SS-WeP17, 26 Yeon, S.H.: SC+EL+SS-WeP16, 26 Yi, S.I.: SC+EL+SS-WeP21, 27 Yoo, H.J.: MI+EL-WeA5, 31 Yoo, J.B.: SC+SS+EL-ThA7, 42 Yoo, J.-H.: DI+EL+MS-WeA5, 29 Yoon, M.: DI+EL+MS-WeA8, 30; SC+EL+SS-MoA5, 3 Yoshigoe, A.: SC+EL+SS-WeP8, 25 Youn, S.: EL-TuP3, 15 Yu, E.T.: SC+EL-FrM8, 45 Yu, J.: EL+NS-TuM8, 6 Yu, K.-S.: SC+EL+SS-WeP16, 26 Yudin, S.G.: OF+EL+SS-ThM11, 38

— Z — Zahidi, E.M.: OF-WeP12, 23 Zandvliet, H.J.W.: SC+EL+SS-WeA5, 32 Zapien, J.A.: TF+EL-WeA7, 34 Zavada, J.M.: SC+EL-FrM7, 44 Zetterling, C.-M.: SC+EL+SS-WeP13, 26 Zhang, A.P.: SC+EL-FrM1, 44; SC+EL-FrM10, 45 Zhang, X.: DI+EL+MS-ThM1, 35 Zharnikov, M.: SS2+NS+BI+EL-TuM2, 9; SS2+NS+BI+EL-TuM9, 10 Zhou, G.: EL-TuP6, 15 Zhou, X.: OF-WeP3, 22 Zhu, X.-Y.: OF+EL+SS-WeM4, 21 Zinck, J.J.: SC+EL+SS-TuM1, 7 Zocco, T.: SS2+EL-MoA5, 5 Zoethout, E.: SC+EL+SS-WeA5, 32 Zorba, S.: EL+NS-TuM6, 6; OF-WeP10, 23