### Surface Engineering Room 201 - Session SE+TF-MoM

### Hard and Superhard Coatings

Moderator: A. Inspektor, Kennametal Inc.

8:20am SE+TF-MoM1 Plasma Deposition of Hard and Thermal Resistant Coatings in the System Si-B-C-N, D. Hegemann, C. Oehr, Fraunhofer Institute for Interfacial Engineering and Biotechnology, Germany; R. Riedel, Technical University Darmstadt, Germany; H. Brunner, Fraunhofer Institute for Interfacial Engineering and Biotechnology, Germany

As a result of covalent bonding, the four elements boron, carbon, nitrogen and silicon can form superhard materials. Considering the well-known diamond-like and cubic boron nitride films, which are limited by their temperature resistance and adhesion, respectively, further research in the as before mentioned system is required. Thus, BCN and SiBCN thin films are very promising candidates which are therefore investigated. A capacitive rf discharge in an asymmetrical but confined geometry is chosen for the deposition experiments to sustain well defined plasma conditions. The bias voltage depending on delivered power and pressure is taken as control parameter. Due to the use of single-source precursors - pyridine borane and (PB) triazaborabicyclodecane (TBBD) for BCN, tris(dimethylamino)silylamino-bis(dimethylamino)borane (TDADB) for SiBCN - relative low substrate temperatures (300°C) can be applied yielding amorphous films. Ar or N@sub 2@ in an excess of 50:1 serves as carrier gas. Both with BCN and SiBCN film deposition, several regimes of different chemical composition become apparent increasing the bias voltage. An influence of the used precursor is merely observed at low biases. At moderate bias voltages films comparable to thermal CVD processes are obtained. Further increasing the bias yields hard coatings up to 13.5 GPa and 30.8 GPa measured by microindentation for BCN and SiBCN, respectively. It is found that the hardness scales mainly with the carbon content of both films, analogously. Annealing the films for 5 h in argon or air exhibits a thermal and oxidation resistance of the SiBCN films exceeding 1200°C. On the other hand, BCN films start to decompose at about 1000°C in argon and 800°C in air. Moreover, the SiBCN films show lower internal stresses (1-2 GPa) compared to BCN, which is attributed to a stabilization effect of sp@super 3@ hybridized carbon by silicon incorporation.

#### 8:40am SE+TF-MoM2 Structure and Mechanical Properties of Ti-Si-C Coatings Fabricated by Sputtering and Pulsed Laser Deposition, S.H. Koutzaki, J.E. Krzanowski, University of New Hampshire; J. Nainaparampril, Systran, Inc.; A.R. Phani, University of New Hampshire

Nano-structured coatings consisting of mixtures of carbide compounds can provide a useful route to developing super-hard materials. Heterogeneous nano-structured coatings can be obtained by either deposition of multilayer structures or by depositing film compositions that undergo a natural phase separation due to thermodynamic immiscibility. In the present work, we have taken the latter approach, and deposited films by RF co-sputtering from dual carbide targets, as well as by pulsed-laser deposition (PLD) using ternary carbide targets. We have examined a number of ternary carbide systems, and to date the most promising coatings have been obtained in the Ti-Si-C system. In this system, the TiC and SiC phases are highly immiscible and phase separation on deposition is likely to occur. We first examined sputter-deposited TiC coatings with varying SiC content. It was found that the nano-indentation hardness increased with SiC content, with a maximum hardness nearly twice that of the sputtered-deposited TiC films at a SiC content of 15 at. %. We further analyzed these films using high-resolution TEM, XPS and X-ray diffraction. Since cubic SiC has an X-ray pattern almost identical to that of TiC, the extent of phase separation could not be determined by that method. However, XRD did demonstrate a general disordering of the films with increasing SiC content. High-resolution TEM also revealed that films of higher SiC content exhibited a mottled structure and nano-scale phase separation within the grains. Further studies were conducted comparing PLD TiC and TiC-12 at.% SiC films (the latter made using a ternary target). The Ti-Si-C coatings exhibited about 25% higher hardness levels in comparison to TiC alone.

9:00am SE+TF-MoM3 Hard and Superhard Coatings - A Review, W.D. Sprou<sup>1</sup>, Reactive Sputtering, Inc. INVITED

Hard coatings such as titanium carbide deposited by the high temperature chemical vapor deposition (CVD) process first made their commercial appearance in the late 1960s. The single layer coatings were soon supplanted with multilayer CVD coatings, but it was difficult to apply these coatings to high speed steel (HSS) tooling or steel alloys without damaging the metallurgical properties of the steel. In the early 1980s, several physical vapor deposition (PVD) techniques became available for depositing hard coatings such as titanium nitride or titanium aluminum nitride onto HSS. One of the driving forces in the PVD coatings business has been a desire to increase the hardness of the coatings with the ultimate goal of matching or exceeding the hardness of diamond. Today superhard (hardness greater than 40 GPa) coatings exist. The hardening mechanisms for achieving superhardness fall into two categories, intrinsic and extrinsic. Intrinsic materials such as diamond, cubic boron nitride, and some ternary compounds rely on high bond energies and short bond lengths to achieve superhardness whereas the extrinsic nanostructured multi-layer and nanocrystalline materials rely on the microstructure to restrict dislocation movement to achieve superhardness. A hardness exceeding that of diamond has been reported for a nanocomposite of titanium nitride and silicon nitride. Coating hardness is only one property that should be considered when engineering a surface. Coating toughness should also be factored in especially in situations where impact loading will occur. Today advances are being made in high-density plasma (HDP) PVD techniques that will have a direct impact on future PVD hard coatings. The high degree of ionization in HDP systems will allow new compounds synthesis at temperatures well below the thermodynamic equilibrium point. Perhaps in the near future crystalline alpha alumina will be deposited below 500 degrees C by HDP PVD techniques.

### 9:40am SE+TF-MoM5 Unbalanced Magnetron Sputter Deposition of Al-Ti Ceramic Coating for High Speed Milling Application, *X. Zeng*, Gintic Institute of Manufacturing Technology, Singapore

Hard coatings for high speed machining consist of multiple layers because of the requirements for high adhesion strength to the substrate, high thermal stability, high hardness and low friction coefficient and good compatibility. Traditionally used coatings like TiN, CrN and their alloyed nitride coatings have high hardness and good adhesion on common tooling materials used in industry. However, these coatings usually have poor performance in high speed machining applications, especially in the cutting of hardened tool steels, because of phase transition (oxidation) at high temperatures. Ti-Al alloyed nitrides seem to be one of the most promising coatings for this application due to its high thermal stability, low friction coefficient and high hardness. This paper reports the development of a multilayered Ti-Al ceramic hard coating on tunsten carbide ballnose endmills for high speed milling using an unbalanced magnetron sputtering system @footnote 1@. The process parameter dependence of the coating properties was studied. X-ray diffractometry, x-ray photoelectron spectroscopy, nanoindentation and scratch test were used to characterize the structural, compositional and mechanical properties of the coatings. High hardness, up to 40 GPa, good adhesion strength, up to 100 N in scratch critical load, and high oxidation resistance were achieved, leading to excellent performance in high speed milling on hardened tool steel at a machining speed of 260 m.min@super -1@. The results show that the tool life with this coating is improved by a factor of 4 or better, under the testing conditions used, compared to the uncoated WC tools. The surface finish of the machined steel achieved with this coating is also significantly better. @FootnoteText@ @footnote 1@ X.T. Zeng, J. Vac. Sci. Technol., A 17, (1999) 1991

## 10:00am SE+TF-MoM6 Thermal Stability and Mechanical Properties of Nano-scale W/ZrN Multilayers, A. Madan, Northwestern University; J. Ji, S.A. Barnett, Applied Thin Films, Inc.

Nanolayered thin films show an enhanced hardness and improved mechanical properties as compared to the individual layer components. The high-temperature stability of these films is important for various technological applications e.g. dry-cutting. We report on the thermal stability and mechanical properties of polycrystalline, immiscible W/ZrN nanolayered films. W/ZrN multilayers of bilayer periods 2 to 40 nm were sputter deposited in a dual-opposed-cathode unbalanced-magnetron sputtering system. The W fraction was varied from 0.3 to 0.8 by adjusting the relative power on the two targets. The 1 micron films were annealed at

1

temperatures from 750°C to 1000°C in inert atmospheres. The as-deposited and the annealed films were characterized using x-ray diffraction, crosssectional transmission electron microscopy (XTEM), and nanoindentation. The as-deposited films showed an enhanced hardness in comparison to the rule-of-mixtures values irrespective of the bilayer period or the layer composition ratio. High- and low-angle x-ray diffraction (XRD) showed that the layered structure was stable after annealing at 1000°C for 1 h. XTEM results for as-deposited and annealed films will be presented. The annealed films show hardnesses as high as 44 GPa. The excellent high-temperature stability of the W/ZrN nanolayered structures arises because W and ZrN are mutually immiscible.

### 10:20am SE+TF-MoM7 Growth and Characterization of ZrN/ZrB@sub 2@ Nanolayered Coatings for High Temperature Applications, K Martin, J. Ji, I. Kim, S.A. Barnett, Applied Thin Films, Inc.; A. Madan, Northwestern University; P. Hedge, A. Inspektor, Kennametal, Inc.

There is a great need for cutting tool coatings that perform well at elevated temperatures, both because of the desire to cut at higher rates and to eliminate coolant fluids. However, current cutting-tool coating materials fail rapidly under these conditions because of poor high-temperature properties. The ZrN/ZrB@sub 2@ nanolayered system is expected to provide a unique combination of properties including high hardness, excellent stability at elevated temperatures, low chemical solubility in Fe and good thermal expansion match with cemented carbide tools. In this investigation, ZrN/ZrB@sub 2@ nano-layered coatings were deposited using a dual-cathode magnetron sputtering system. The key properties including hardness, adhesion, and residual stress were evaluated as a function of composition, bilayer period, and substrate bias. The hardness values for as-deposited coatings ranged from 30-38 GPa and increased to 49 GPa after annealing at 1000°C. Low and high angle XRD revealed that the superlattice structure was stable at elevated temperatures. The increase in hardness after annealing is attributed to the transition of the soft amorphous ZrB@sub 2@ to the crystalline form. Adhesion testing verified that the coatings adhered well on cemented carbide inserts even after annealing at 1000°C.

### 10:40am SE+TF-MoM8 Fabrication of Al-Pt Coating on Ni Base Superalloys and Studies of Their Structure, *M. Ghoranneviss, H. Parchamy Aragy,* Islamic Azad University, Iran; *A. Sedghi,* International Iran Khomani University, Iran; *A. Shokohi,* Islamic Azad University, Iran

Thin film coating are formed on the enginneering materials to improve their physical and mechanical properties these coating are used mainly in different fields of industrial application and in these respect many research to improved their properties.In projects conducted this research, therefore, the formation of Al-Pt(Aluminum/Platinum) alloys coatings on nickel based super alloys has been studied.Sputtering-ion beam technique under Argon plasma and subsequent heat treatment is been used to fabricate these coating.Ion implantation is applied the Aluminum-Platinum alloys coatings. The main goal of this work is increasing erosion and consequently erosion-corrosion resistance of these coating. Scan Electron Microscope, Glow discharge Spectrometers and X-Ray Diffraction techniques is used to investigate the structure of fabricated coatings. These results correlates with other investigations and these method can be presented as a industrial method for fabrication of these coating.lon implantation improved these properties but the results not very appreciable.Details will discus in full paper.

### **Surface Science**

### Room 209 - Session SS2+NS+TF-MoM

### Nucleation and Growth

Moderator: G.L. Kellogg, Sandia National Laboratories

8:40am SS2+NS+TF-MoM2 Homoepitaxial Growth of Ni on Ni(110) : Surface with Anisotropic Diffusivity and Energy Barriers, B.-Y. Choi, Seoul National University, Korea; S.-J. Kahng, University of Illinois at Urbana-Champaign; J.-Y. Park, Y. Kuk, Seoul National University, Korea

The homoepitaxial growth of Ni was studied on Ni(110) surface with scanning tunneling microscopy. The Ni(110) surface does not reveal surface reconstruction, but it has corrugated channels along the [1 - 1 0] direction and the resultant surface diffusion anisotropy. Homoepitaxial islands grow with high aspect ratio, as large as 1:1000, due to i) the diffusion anisotropy and ii) the energy barrier from an [1 - 1 0] side wall to an [001] side wall around the adatom islands. The aspect ratio of the islands decreases with increasing temperature. The competition between these two mechanism

will be discussed. At the high coverage (@>=@10ML), the aspect ratio decreases substantially and the growth structure transforms to 3D islands without asymmetry. At these coverage, the surface roughness saturates. Although the microscopic origin is unclear, the phenomenon can be explained with a KPZ type equation with some modifications.

9:00am SS2+NS+TF-MoM3 Thermodynamics of Thin Film Alloys: Experimental and Theoretical Study of Ag and Co on Ru(0001), G.E. Thayer, University of California, Davis; A.K. Schmid, V. Ozolins, N.C. Bartelt, Sandia National Laboratories; S. Chiang, University of California, Davis; R.Q. Hwang, Sandia National Laboratories

It has long been known that the structure of materials in thin film configurations can differ significantly from their bulk phase. This is particularly true of alloy films. It has recently been shown that strain induced by the lattice mismatch between substrate and film can lead to the formation of novel alloys that do not exist in the bulk. One prototypical example is the system of one monolayer Ag/Co films grown on Ru(0001). In the bulk, Ag and Co are immiscible. However, on the Ru surface alloy phases of distinct stoichiometries are formed. We have investigated the phase diagram of 1ML AgCo/Ru(0001) films using scanning tunneling microscopy (STM) and first principles calculations. For Ag rich films, segregation between a pure Ag phase containing dislocations and a pseudomorphically strained alloy of stoichiometry Co@sub 0.6@Ag@sub 0.4@ is found. The driving force for the phase segregation is the competition between two strain relief mechanisms: dislocation formation and alloying. In the Ag saturated Co@sub 0.6@Ag@sub 0.4@ alloy, atomic resolution STM images show that the alloy consists of a Co film containing disordered, elongated Ag droplets with an average size of 30 atoms separated by an average distance of 10 Co atoms. As the composition of Ag in the film is decreased, the Ag droplets become more uniform in size and decrease to an average minimum size of 10 atoms. Simultaneously, the distribution of the droplets becomes uniform and dilute. This behavior has been predicted using first principles, local density approximation (LDA) calculations. These calculations, together with atomically resolved STM images, have quantified configuration energies for various stoichiometries of this system. This investigation has led to a quantitative interpretation of the competition between the chemically repulsive interaction of Ag and Co (also seen in their bulk miscibility gap) and the strain fields in the thin film alloy that they form.

#### 9:20am SS2+NS+TF-MoM4 Theory of the Nucleation and Growth of Iron on GaAs, S.C. Erwin, Naval Research Laboratory; M. Scheffler, Fritz Haber Institute, Germany

By growing ultrathin films of ferromagnetic metals on semiconductor substrates, it is possible to create a partially spin-polarized electrical current in the semiconductor. This phenomenon is the starting point for a wide variety of magnetoelectronic devices based on the "spin-valve" effect. whereby an externally applied magnetic field can switch the current on and off. Considerable experimental effort has focused on ultrathin films of Fe grown by MBE on GaAs, in part because their small lattice mismatch results in nearly epitaxial films. Although a number of experiments have contributed to a detailed description of the phenomenology of magnetism in these films, little is known about the microscopic physics of magnetism at an intimate metal-semiconductor interface. We use spin-polarized density-functional total-energy methods to investigate the nucleation and initial growth phases of Fe on GaAs(001), focusing on the roles played by diffusion, magnetism, and defect chemistry. Our findings include the following results: (1) magnetism develops in the very first monolayer, and is in fact enhanced by the presence of the interface; (2) surface diffusion is strongly suppressed in the submonolayer regime by the tendency of Fe adatoms to form very stable Fe-As bonds. Finally, we discuss the influence of the initial GaAs reconstruction on the structure and magnetic properties of the Fe film.

### 9:40am SS2+NS+TF-MoM5 Nucleation and Growth in Metal-on-Metal Epitaxy - Complications beyond Simple Systems, R.J. Behm, University of Ulm, Germany INVITED

The quantitative atomic scale understanding of a surface process, as a sequence of elementary steps, is one of the primary objectives in Surface Science. Molecular beam epitaxial growth (MBE) is one the first areas where extensive and systematic studies, both experimental and theoretical, have led to such kind of understanding, at least for simple processes such as nucleation and two-dimensional growth on inert, bare and non-reconstructed substrates.@footnote 1@ In this talk I will focus on complications which arise when these conditions are not fulfilled, predominantly on the effect of coadsorbed species on nucleation and

growth processes. These coadsorbates, which are generally present, e.g., in the case of chemical vapor deposition (CVD), are shown to affect not only the nucleation behavior, but may lead also to the formation of new, (metastable) film structures. A second topic to be discussed involves nucleation and growth on 'instable' surfaces, where growth competes with exchange processes and surface alloy formation. On such systems and under certain conditions metal deposition was found to cause a severe restructuring of the substrate, leading to pit formation. Mechanistic ideas will be presented and discussed. @FootnoteText@@footnote 1@H. Brune, Surf. Sci. Rept. 31, 121 (1998).

## 10:20am SS2+NS+TF-MoM7 Preferential Nucleation of Metal Nanoclusters on S(4x4)/W(111), Q. Wu, W. Chen, T.E. Madey, Rutgers, The State University of New Jersey

Interactions of several metals (Cu, Pt and Pd) with the highly ordered S(4x4)/W(111) surface have been studied by means of Auger electron spectroscopy (AES), low energy electron diffraction (LEED), and scanning tunneling microscopy (STM). The substrate is a sulfur-induced nanoscale reconstruction of W(111) with (4x4) periodicity, characterized by broad, planar terraces (~ 30 nm in width). We find that fractional monolayers of vapor-deposited Cu grow as 3D clusters on the S(4x4) surface over a wide coverage range. At low Cu coverages (@<=@ 0.1 ML), Cu nanoclusters are observed to nucleate preferentially at characteristic 3-fold hollow sites on the S(4x4) surface; there is a clear energetic preference for one type of site over others. The formed Cu nanoclusters are uniform in size (~ 0.7 nm) up to 0.25 ML, indicating self-limiting growth. As coverage increases, additional sites are populated and Cu clusters grow in size. On the other hand, Pt and Pd exhibit a different behavior, disordering the (4x4) reconstruction and adsorbing beneath the outer S-layer. STM data are supported by LEED and AES measurements. The data are interpreted in terms of relative surface free energy, relative reactivity, and the metal-W, metal-S, and S-W binding energies, as supported by our previous TPD data.

## 10:40am SS2+NS+TF-MoM8 Ultra-thin Al Films Grown Epitaxially on CaF@sub 2@/Si(111), Y.V. Shusterman, N.L. Yakovlev, L.J. Schowalter, Rensselaer Polytechnic Institute

Electron scattering at metal boundaries becomes increasingly important as interconnect structures shrink further. To improve our understanding of this phenomenon, studies of electron transport through ultra-thin metal films are needed. In such experiments, it is desirable to have smooth, single crystal metal layers grown on an insulating substrate. For this reason, we are studying epitaxial growth of Al on CaF@sub 2@/Si(111), with metal thickness as low as several nanometers. The structures discussed in this work were grown by molecular beam epitaxy and investigated by reflection high-energy electron diffraction (RHEED), scanning tunneling microscopy (STM) and atomic force microscopy (AFM). Hydrogen-terminated Si(111) was used as a substrate. The CaF@sub 2@/Si interface was formed at 700°C, followed by fluoride overgrowth at temperatures below 200°C, which resulted in improved continuity of the subsequent Al layer. The roughness of the final CaF@sub 2@ surface was below 1nm. as measured by AFM. The Al films grew epitaxially, as revealed by RHEED patterns that only contained streaks. The spacing between the streaks from Al was about 4/3 times larger than that from CaF@sub 2@, in agreement with bulk lattice mismatch. The growth proceeded through formation of 3dimentional islands that then coalesced as the thickness increased. Using an Al deposition rate above 1nm/s at room temperature, we were able to obtain continuous films as thin as 10nm with roughness less then 2nm. The STM images of these films showed atomic steps, some of them originating at screw dislocations. The density of these dislocations was around 10@super 11@ cm@super -2@. The dependence of Al conductivity on film thickness will also be presented.

### Thin Films

Room 203 - Session TF-MoM

### Atomic Layer Chemical Vapor Deposition I Moderator: S.M. George, University of Colorado

8:20am TF-MoM1 Atomic Layer Deposition of Microelectronic Materials: The Present Status and Future Challenges, *M.K. Ritala*, University of Helsinki, Finland INVITED

As the evolution towards increasing integration densities continues in the integrated circuit manufacturing, new materials and thin film deposition methods will inevitably be needed. Atomic Layer Deposition (ALD) is one of the most promising film deposition techniques capable of meeting the

strict requirements in future generation IC manufacturing. The self-limiting film growth mechanism of ALD ensures excellent conformality and uniformity over large areas, and atomic level composition and thickness control. In this paper, the present state of ALD of materials of an interest to microelectronics will be reviewed, including also the current understanding of the related chemistry, and challenges for the future research will be outlined. At present, there already exist many potential ALD processes for the following microelectronic materials: dielectrics (e.g. SrTiO@sub 3@, BaTiO@sub 3@, Ta@sub 2@O@sub 5@, Nb@sub 2@O@sub5@, ZrO@sub 2@, HfO@sub 2@ and Al@sub 2@O@sub 3@, and their multilayers and mixtures) for gate oxides and DRAM capacitors, and nitride (e.g. TiN, TaN, NbN, W@sub 2@N) diffusion barriers for metallizations. In addition, some metal (W, Ti, Ta, Cu) ALD processes have been reported as well. Further development of ALD will require increasing efforts in precursor chemistry supported by improved understanding of the growth mechanisms. For the latter, different approaches may be taken. Here a recently developed ALD-QMS-QCM setup enabling in situ characterization of ALD processes under the practically important flow type reactor conditions will be briefly introduced.

## 9:00am TF-MoM3 Atomic Layer Deposition of BN Using Sequential Exposures of BCl@sub 3@ and NH@sub 3@, J.D. Ferguson, S.J. Ferro, S.M. George, University of Colorado

BN is an inert insulating material with a very high thermal conductivity that is desirable for many applications. Atomic layer deposition (ALD) is a useful method for growing ultrathin and conformal films. BN ALD was accomplished by separating the binary reaction BCl@sub 3@ + NH@sub 3@ --> BN + 3 HCl into two half-reactions: A) BNH\* + BCl@sub 3@ --> BNBCl@sub 2@\* + HCl; B) BCl\* + NH@sub 3@ --> BNH@sub 2@\* + HCl. BN films were grown on high surface area SiO@sub 2@ particles using alternating exposures of BCl@sub 3@ and NH@sub 3@ at 700 K. The sequential surface chemistry was monitored in a vacuum chamber using in situ transmission Fourier transform infrared (FTIR) vibrational spectroscopy. The initial SiO@sub 2@ surface contained SiOH\* surface species. The first BCl@sub 3@ exposure reacted with the SiOH\* species to form SiOBCl@sub x@\* species. The subsequent NH@sub 3@ exposure converted the surface species to BNH@sub 2@\*. The following BCl@sub 3@ and NH@sub 3@ exposures converted the surface to BCl@sub x@\* and BNH@sub 2@\* species, respectively. By repeating the sequential surface reactions, BN bulk vibrational modes on the SiO@sub 2@ particles increased versus number of AB cycles. In addition, spectroscopic ellipsometry studies of BN ALD on Si(100) measured BN growth rates of ~2.5 Å per AB cycle. Transmission electron microscopy also examined the conformality of the BN films on the SiO@sub 2@ particles.

## 9:20am TF-MoM4 Thermal Stability of Si and C Atomic Layers Formed on Ge(100) in Silane and Methylsilane Reactions, *M. Fujiu*, *M. Sakuraba*, *T. Matsuura*, *J. Murota*, Tohoku University, Japan

In order to realize an atomic layer superlattice of group IV semiconductors, self-limited control of adsorption and reaction of reactant gases and suppression of the mutual diffusion at the hetero interfaces are essential. In this work, thermal stability of Si and C atomic layers formed on Ge(100) in SiH@sub 4@ and CH@sub 3@SiH@sub 3@ reactions was investigated using XPS by an ultraclean low-pressure CVD system. With CH@sub 3@SiH@sub 3@ reaction on Ge(100) at 18Pa, the concentration of Si deposited on Ge(100) was nearly the same as that of C during the reaction at the temperature of 550@super o@C or lower. Especially at 450@super o@C, single atomic layers of Si and C were formed self-limitedly on Ge(100). When the single atomic layers were subsequently annealed for 60 min at 600@super o@C, the C atom concentration decreased from the single atomic layer to about half of the atomic layer, although the Si atom concentration hardly changed. The result suggests that the Si-C bond is gradually broken by annealing at 600@super o@C, and the C atom desorbs. On the other hand, with SiH@sub 4@ exposure on Ge(100) at 120Pa, the deposited Si concentration saturated to that of the single atomic layer at 300@super o@C. After formation of the Si single atomic layer on Ge(100) followed by further annealing for 60 min at 500@super o@C and subsequent SiH@sub 4@ exposure for 30 min at 300@super o@C, the deposited Si concentration increased and reached to 120% of the Si single atomic layer. It is suggested that atomic order mixing occurs even at 500@super o@C at the interface between the Si atomic layer and the Ge substrate, and the segregated Ge atom enhances the further SiH@sub 4@ reaction on the surface. The above results reveal that the atomic order mixing is greatly suppressed by the existence of C atoms on the surface. The dependence of the growth and annealing temperatures on the thermal stability of Si and C atomic layers on Ge(100) will be presented.

9:40am TF-MoM5 Selective Growth of ZnO Thin Film on Microprinted Si Substrate, M. Yan, R.P.H. Chang, J. Ni, J.R. Babcock, T.J. Marks, Northwestern University INVITED

ZnO is an inexpensive transparent conductive material that has already received intensive studies. Recently, its interesting optical property has made it a potential LED material. Various techniques, including chemical vapor deposition (CVD), sputtering, pulse laser deposition (PLD) and atomic layer epitaxy (ALE), have been used to deposit ZnO thin film onto different substrates. In order to make devices, patterned ZnO film has to be achieved. Typically, features can be fabricated using photolithography. For mass production, however, a low cost and high throughput method is needed. In this research, ZnO thin film was deposited onto microprinted Si substrate using ALE. 1-trichlorosilyl-docosane(CH@sub 3@(CH@sub 2@)@sub 21@SiCl@sub 3@) and perfluorodecyl-1H,1H,2H,2Htrichlorosilane(CF@sub 3@(CF@sub 2@)@sub 7@CH@sub 2@CH@sub 2@SiCl@sub 3@), both of which have a long hydrophobic alkyl chain, were used as ink in microprinting. The -SiCl@sub 3@ group in the above compounds can react with the -OH groups on the surface of Si substrate, thus the hydrophobic chain was fixed on the surface of Si. Water and diethylzinc (DetZn) were used as precursors in ALE. Since water can not stick to the areas that have been covered with ink. selective growth of ZnO can be achieved. Preliminary study shows that selective growth of ZnO has been realized on microprinted Si substrates, which has feature size of 50ï•-m. Optical and Scanning Electronic Microscopy (SEM) observations show that features have satisfactory sharpness. Discussion of low temperature ALE of ZnO on different substrate, such as glass and flexible polyethylene terephthalate (PET), will be reported.

## 10:20am TF-MoM7 Electrical Characterization of Ultrathin Al@sub 2@O@sub 3@ Films Grown by Atomic Layer Deposition in a Viscous Flow Reactor, *M.D. Groner*, *J.W. Elam, S.M. George*, University of Colorado

Al@sub 2@O@sub 3@ is an important insulator and is a candidate to replace SiO@sub 2@ as a gate dielectric in MOSFETS. Al@sub 2@O@sub 3@ films were deposited by atomic layer deposition (ALD) using alternating exposures of trimethylaluminum and H@sub 2@O on a variety of substrates. The films were grown in a custom viscous flow reactor employing a novel gas pulse switching method. The film growth was monitored in situ by a quartz microbalance and ex situ using ellipsometry. The electrical properties of the A l@sub 2@O@sub 3@ films were evaluated by performing I-V and C-V measurements with a mercury microprobe. The highest quality ALD Al@sub 2@O@sub 3@ films were obtained using ultraclean Si(100) substrates or molybdenum substrates. The ALD Al@sub 2@O@sub 3@ films exhibited extremely low leakage current levels. The electrical properties of the ALD Al@sub 2@O@sub 3@ films deposited on molybdenum were examined versus Al@sub 2@O@sub 3@ thickness from 30 Å to 2400 Å. The C-V measurements revealed that the dielectric constant was k=7.8 for Al@sub 2@O@sub 3@ films @>=@ 1200 Å. The dielectric constant decreased below 100 Å to k=4.0 at 25 Å. The I-V measurements showed that the Fowler-Nordheim (FN) tunneling onset voltage decreased with Al@sub 2@O@sub 3@ film thickness. The onset of FN tunneling occurred at >10 V for 600 Å films and at ~3.5 V for 60 Å Al@sub 2@O@sub 3@ films.

## 10:40am TF-MoM8 A Study on the Characteristics of TiAlN Thin Film Deposited by Atomic Layer Chemical Vapor Deposition Method, *H. Jeon*, *J.W. Lee*, *J.H. Koo*, *T.H. Doh*, *Y.D. Kim*, Hanyang University, South Korea

Atomic Layer Chemical Vapor Deposition(ALCVD) method is one of the new deposition method to grow very thin films.@footnote 1@ Conventional PVD and CVD methods exhibit problems such as poor step coverage, impurity contamination and particle generation. ALCVD method has a lot of advantages over other CVD processes and these are excellent thickness uniformity, conformal step coverage, very low pinhole density, and elimination of particle generation by gas phase complete reaction.@footnote 2@ The sequential control of the growth in ALCVD system is based on saturating surface reactions between the substrate and each of the reactant needed for the compound to be grown. Each surface reaction adds full or partial fraction of monolayer of the material on the surface. Here we deposited TiAIN ternary diffusion barrier by ALCVD method. Ternary diffusion barrier is considered to be more efficient than binary diffusion barrier such as TiN. But ternary film of Ti-Si-N has high resistivity to apply for actual process. In this study we deposited TiAIN ternary diffusion barrier to study the diffusion barrier characteristics.@footnote 3@ TiCl@sub 4@ vapor, DMAH-EPP vapor, and NH@sub 3@ gas were alternatively introduced into reactor to form TiAIN by ALCVD. The physical and chemical properties of TiAIN films were analized by TEM, AES, RBS, and SEM. The growth mechanism will be Monday Morning, October 2, 2000

discussed based on the results of characteristics of TiAlN. @FootnoteText@ @footnote 1@T. Suntola, Thin Solid Films, 216, 84-89(1992) @foontote 2@S. Yokoyama, H. Goto, T. Miyamoto, N. Ikeda, K. Shibahara, Applied Surface Science, 112, 75-81(1997) @footnote 3@ C. W. Kim, K. H. Kim, Thin Solid Films, 307, 113-119(1997).

### Monday Afternoon, October 2, 2000

### Thin Films Room 203 - Session TF-MoA

### Atomic Layer Chemical Vapor Deposition II

Moderator: S.M. Rossnagel, IBM T.J. Watson Research Center

## 2:00pm TF-MoA1 The Effect of Atomic Layer CVD Flow Parameters on the Growth Orientation of AIN Thin Films, J.N. Kidder, J.W. Rogers, T.P. Pearsall, University of Washington

We have observed a strong dependence of growth orientation on reactant pulse length in an atomic layer CVD of AlN. The AlN thin films were deposited on Al@sub2@O@sub3@ and Si substrates at 523-723 K and 25 Torr using an amine-alane Al source. The Al precursor, dimethylethylamine alane (DMEAA) and ammonia were delivered to the growth surface in separate steps. Strict self-limited adsorption did not occur for the DMEAA at these process conditions but a kinetic barrier to rapid decomposition of DMEAA coupled with process flow control provided a means to generate film formation through a sequence of adsorption/reaction steps. We observed that film microstructure was strongly dependent on ALCVD pulse lengths and substrate temperature. By this process, crystalline AIN films were deposited at temperatures as low as 573 K. AIN films deposited on Si(100), Si(111), Al@sub2@O@sub3@(00.1) tended to show a preferred orientation with the AIN{00.1} planes aligned parallel to the substrate surface. AIN{11.0}oriented growth was observed on Al@sub2@O@sub3@(01.2)substrates. The growth orientation was strongly dependent on the pulse length and substrate temperature. Both well-oriented random and films were deposited on Al@sub2@O@sub3@(00.1). By varying the reactant flow sequence the growth orientation on Al@sub2@O@sub3@(01.2) could be controlled to be either AIN{00.1} or AIN{11.0} oriented. X-ray four circle diffractometry scans showed in-plane orientations associated with epitaxial alignment for films deposited at temperatures as low as 673 K. These results illustrate the potential for using sequential reactant delivery in CVD to tailor the microstructure of thin film materials.

### 2:20pm TF-MoA2 Atomic Layer Deposition (ALD) Films for Advanced Capacitors, O. Sneh, R.C. Phelps, T. Seidel, Genus, Inc.

We will present new data on Atomic Layer Deposition (ALD) films. Films were deposited on our recently announced dielectric ALD processing module. Our ALD process equipment, now at beta phase, is a single wafer 200 mm process module that operates and fully integrates with Genus Lynx2 cluster tool. Data pertain for as deposited, fully stoichiometric Al@sub 2@O@sub 3@ and Ta@sub 2@O@sub 5@ films that are continuous and amorphous in the useful range of 15-200 Å, will be presented. CV and IV measurements indicate leakage current in the 10@super -8@ A/cm@super 2@ range for these films in the useful thickness range and dielectric constants of ~7.5 (Al@sub 2@O@sub 3@) and ~25 (Ta@sub 2@O@sub 5@). Step coverage over >15:1 aspect ratio structures with 100 nm width is 100 %. Supporting data will be presented and discussed. We will review data for dielectric films on silicon as well as over CVD and ALD deposited metal nitride thin films. Some aspects and applications of MIM and SIS capacitor technology development will be reviewed.

2:40pm TF-MoA3 Tungsten Atomic Layer Deposition: Nucleation and Growth on Oxide Surfaces, S.M. George, J.W. Klaus, J.W. Elam, C.E. Nelson, R.K. Grubbs, S.J. Ferro, University of Colorado INVITED Tungsten atomic layer deposition (ALD) can be accomplished by separating the binary reaction WF@sub6@ + Si@sub2@H@sub6@ --> W + 2SiHF@sub3@ 2H@sub2@ into self-limiting + two halfreactions.@footnote 1@ The two self-limiting half-reactions are: (A) W-SiHF@sub2@\* + WF@sub6@(g) --> W-WF@sub5@\*+ SiHF@sub3@(g); and (B) WF@sub5@\* + Si@sub2@H@sub6@(g) --> W-SiHF@sub2@\* + 2H@sub2@(g) + SiHF@sub3@(g). In situ FTIR spectroscopy studies have determined the temperatures and pressures required for these two halfreactions to reach completion. In situ spectroscopic ellipsometry studies have examined the growth of W ALD films. Successive exposure to WF@sub6@ and Si@sub2@H@sub6@ in an ABAB... reaction sequence produced W ALD at a rate of 2.5 Å per AB cycle at 425 K. The nucleation and growth during W ALD on SiO@sub2@ and Al@sub2@O@sub3@ surfaces have also been studied using Auger electron spectroscopy (AES). The AES results displayed an initial nucleation period of several AB cycles. After the deposition of one tungsten monolayer, the AES signals for W and Si oscillated dramatically versus WF@sub6@ and Si@sub2@H@sub6@

exposures. These studies indicated that W ALD displays nearly ideal layerby-layer (Frank van der Merwe) growth after the initial nucleation period. W ALD can be used together with Al@sub2@O@sub3@ ALD@footnote 2@ fabricate W/Al@sub2@O@sub3@/W/Al@sub2@O@sub3@ to nanolaminates. Cross-sectional transmission electron microscopy (TEM) studies have examined the W/Al@sub2@O@sub3@/W/Al@sub2@O@sub3@ nanolaminates deposited on Si(100). The growth of the nanolaminates is dependent on the details of the surface chemistry during the nucleation of W ALD on Al@sub2@O@sub3@. @FootnoteText@ @footnote 1@ J.W. Klaus, S.J. Ferro and S.M. George, Thin Solid Films 360, 145 (2000). @footnote 2@ A.W. Ott, J.W. Klaus, J.M. Johnson and S.M. George, Thin Solid Films 292, 135 (1997).

#### 3:20pm TF-MoA5 Radical Enhanced Atomic Layer Deposition (ALD) of Diffusion Barrier Films at Low Temperatures, A. Sherman, F. Turner, Sherman & Associates; C. Pan, ASM America; S.M. Rossnagel, IBM T.J. Watson Research Center INVITED Atomic Layer Deposition (ALD) processes can be extended to low deposition temperatures by the use of an appropriate free radical in place of a conventional molecular reactant. Typically, the ALD process has been carried out using stable gaseous reactants, and the surface reaction was thermally driven in the temperature range of 300-400°C. Radical enhanced ALD has been carried out for the deposition of Ti, TiN, Ta, TaN, and Al@sub 2@O@sub 3@ at temperatures from room temperature to 400°C. Remote inductive plasma sources, operating at frequencies from 400 KHz to 13.56 MHz were used to generate free radicals from O@sub 2@, N@sub 2@, H@sub 2@ and NH@sub 3@ gas sources. Residual gases in the reactor chamber were removed after each dosing step by evacuating the chamber with a vacuum pump, rather than purging with an inert gas. Titanium films were deposited from 25-250°C using titanium tetrachloride and hydrogen. The conformality in high aspect ratio vias and the thickness uniformity across 200 mm wafers was excellent. Tantalum films were deposited using tantalum pentachloride and hydrogen at temperatures from 25-400°C. Additional experiments have been carried out using TDMAT (tetrakis(dimethylamido)titanium) at room temperature to deposit titanium bearing films. Aluminum oxide films were deposited at room temperature from TMA (trimethyl aluminum) and oxygen. Experimental results, including SEM observations in high aspect ratio features, as well as chemical analysis (RBS, XPS, AES) and structural (XRD) measurements will be reported.

#### 4:00pm **TF-MoA7 Vacuum Beam Studies of Radical Enhanced Atomic** Layer Chemical Vapor Deposition, *F. Greer*, *D. Fraser*, *J.W. Coburn*, *D.B. Graves*, University of California, Berkeley

As device dimensions continue to shrink and aspect ratios continue to increase, it will become increasingly difficult to deposit highly conformal thin films for applications such as Cu diffusion barrier layers. Atomic Layer Chemical Vapor Deposition (ALCVD) has been proposed as one way to achieve these highly conformal thin films due to the layer-by-layer growth that is possible when a precursor and a stable reactive specie are introduced sequentially into a deposition chamber. One problem with conventional ALCVD is that the deposition temperatures that are required to achieve reasonable growth rates can be relatively high, and may be incompatible with the integration of these barrier films with temperaturesensitive films such as organic low-k materials.@footnote 1@ It has been recently proposed that by using a more reactive specie like a radical as the second reactant, atomic layer film deposition at lower temperatures may be possible.@footnote 2@ It may also be possible to find radical surface treatments that either promote or hinder adsorption of the precursor specie on different surfaces, allowing even more control over the deposition process. This work focuses on the tetrakisdiethylamide class of precursors for the deposition of nitrides and other films. By directing independent beams of these precursors and hydrogen radicals at different surfaces (inc. Si, SiO@sub 2@, and Au), deposition parameters of interest such as the sticking and reaction probabilities of these compounds have been measured as a function of temperature and surface preparation. The products evolved from the surface during each step of the deposition process, including the precursor ligands and surface reaction products, have also been measured using modulated beam mass spectrometry as a function of these same parameters. XPS analysis of the deposited films will also be presented. @FootnoteText@ @footnote 1@A. Satta et al. Spring MRS Meeting 2000 D6.5 @footnote 2@A. Sherman US Patent 5916365.

### Thin Films Room 203 - Session TF-TuM

#### Thin Films in the 21st Century

Moderator: G.N. Parsons, North Carolina State University

8:20am TF-TuM1 Atomic-Level Control of Microstructure, Morphological Evolution, and Physical Properties during Film Growth: The Golden Era of Materials Science, J.E. Greene, University of Illinois, Urbana INVITED A primary goal of research being carried out worldwide in the area of thin film crystal growth from the vapor phase is the development of the ability to understand, control, and quantitatively model - at the atomic scale surface chemical reaction pathways, growth kinetics, and microstructural evolution. This typically involves operating far from thermodynamic equilibrium in order to selectively open new kinetically-limited reaction paths and has resulted in the development of hybrid growth techniques which combine the inherent advantages of CVD (choice of precursor chemistries for site-specific surface reactions, self-limiting surface terminations, surface-mediated reaction kinetics, surfactant reactions, and conformal coverage), MBE (clean UHV processing compatible with in-situ surface science techniques, and low deposition temperatures), and sputter deposition (the use of hyperthermal particles to overcome surface kinetic barriers). In-situ structural (e.g., RHEED, LEED, STM, AFM) and chemical (e.g., AES, XPS, EELS, STS, TPD) probes coupled with powerful postdeposition analytical techniques such as high-resolution TEM and synchrotron-XRD, RBS, SIMS, and PL have provided the primary tools for rapid experimental progress over the past few years. The corresponding development of efficient computational methods for molecular dynamics, kinetic Monte Carlo, and density functional theory, together with powerful analytical approaches such as level-set schemes which easily handle singularities and higher dimensions, allows robust predictive modeling to proceed in parallel with experiment. Examples of atomic-scale manipulation of film chemistry, surface morphology, epitaxy by driven assembly, and preferred orientation in polycrystalline layers will be discussed. Structure and chemistry can be manipulated at all length scales from nanometer to mesoscopic to continuum through increasingly complex organizational hierarchies.

### 9:00am TF-TuM3 1D Nanostructures: Building Blocks for Nanotechnologies, C.M. Lieber, Harvard University INVITED

One-dimensional (1D) nanostructures, such as nanowires and nanotubes, are critical building blocks that have the potential to impact many emerging and proposed areas of nanoscale science and technology. This presentation will focus on exploiting our fundamental understanding of growth and physical properties of these nanoscale materials to design and assemble rationally functional nanoscale tools and devices. First, the orthogonal assembly of semiconductor nanowires into integrated multi-terminal electronic and optoelectronic devices and the resulting properties of these structures will be described. Second, a new concept for a carbon nanotube based molecular scale computer will be discussed together with proof of concept experiments. Third, critical tools for imaging, sensing and manipulation at the single molecule scale, which are based on the unique mechanical and electromechanical properties of nanotubes, will be discussed.

#### 9:40am TF-TuM5 Challenges for Thin Films in Communications, W.D. Westwood, THINK Films, Canada, Ontario INVITED

Considering the growth rate in both the demand for thin films and the capability to fabricate them over the past 40 years, it is a daunting task to predict the future of thin film technology, even over the next decade. Apart from Zn evaporation for paper capacitors, the main application of thin films for telecommunications prior to 1960 were electroplated Au relay contacts. Sputtering Ta based resistors and capacitors for tone touch telephone frequency generators was the first of a new range of applicatio ns. Today, there are many very demanding applications in integrated circuits and optical components for communication systems; e.g wavelength separation in high speed fiber systems utilizes over 100 oxide layers in interference coatings with a precision of better than 0.1%. The number of deposition methods has greatly increased in the past 40 years; a whole range of techniques involving combinations of physical, chemical and plasma processes are now used to deposit films for specialized applications. In parallel, sophisticated analytical techniques have provided better understanding of the composition and structure of films and the growth processes. Despite these advances, the requirements for control of films remains ahead of the capability and even better methods are required. Will improvements in PVD or CVD methods meet the requirements or will new techniques provide the high yield, high precision processes which are required?

### 10:20am TF-TuM7 The Transition from Thermally-grown SiO@sub 2@ to Deposited Thin Film Alternative Gate Dielectrics, G. Lucovsky, North Carolina State University INVITED

This continued scaling of lateral dimensions of Si field effect transistors to increase device packing densities, and to improve high frequency performance requires proportional decreases in the effective thickness of the gate dielectric. When this equivalent oxide thickness, EOT, is reduced to < 2.5 to 3 nm, direct tunneling emerges as an important factor in device performance and reliability. Direct tunneling at bias voltages for channel inversion exceeds 1A-cm-2 at EOT ~1.5 to1.6 nm, and defines a limitation for thermally-grown SiO@sub 2@ for high power devices. Limitations for portable devices are much more restrictive. The obvious solution for extending EOT to significantly smaller values ~0.5-0.6 nm is to introduce deposited thin film alternative gate dielectrics with higher dielectric constants. This is a formidable task, since the performance and reliability of devices with thermally-grown SiO@sub 2@ derives from i) the low density of defects, trapping sites and fixed charge, at the Si-SiO@sub 2@ interface, and the ii) the low density of electrically-active defects in the SiO@sub 2@ film. Deposited gate dielectrics will then require separate and independent control of the properties of Si-dielectric interface, and the thin film alternative dielectric generally in stacked configurations. Introduction of alternative gate dielectrics will proceed in two steps, i) replacement of SiO@sub 2@ with deposited silicon oxynitride alloys and silicon nitride, extending EOT to ~ 1.1 nm, and then iii) replacement of the dielectrics of i) with metal-oxide and silicate thin films with dielectrics constants in excess of 10. This paper will address issues relevant to single layer and composite structures for both groups of replacement dielectrics identified above.

### 11:00am TF-TuM9 Porous Coatings with Engineered Microstructure, M.J. Brett, University of Alberta, Canada INVITED

Traditional thin film coatings are often optimized for durability, density and uniformity. However, recent opportunities for porous thin films have led to development of new techniques for fabrication of extremely porous coatings with precisely controlled microstructure. One such process is Glancing Angle deposition (GLAD), which combines the features of glancing incidence flux at the substrate with controlled substrate motion. Whereas "normal" evaporated or sputtered thin films usually possess a columnar structure that is densely packed, in the GLAD process extreme self shadowing from nuclei leads to greatly increased separation of columns and growth of isolated microstuctures. Microstructural shape may be tailored by substrate motion to produce, for example, helices, pillars, chevrons, and S-curves with feature sizes from 10 nm to 20 µm. In this manner GLAD has been utilized for simple one-step fabrication of films of high surface area and controlled porosity and structure from dielectric, semiconductor, metal, and alloy materials by sputtering, evaporation, and pulsed laser deposition. Although the stochastic nature of the deposition normally leads to random column nucleation, large area periodically arranged micropost or microhelix arrays may be easily created by deposition over patterned seeds on the substrate. This talk will present details of oblique deposition processes, characterization and description of film microstructures, and results of investigations or of opportunities for the use of engineered porous films in optics, thermal barriers, sensors, magnetics, and as high surface area devices.

#### 11:40am TF-TuM11 Thin Film Technology in the 21st Century, F. Jansen, BOC Edwards INVITED

A century of technology development and materials engineering has provided us with deposition processes for nearly every imaginable material. Interactions between process parameters and materials properties are generally well understood. Today, this allows the controlled deposition and crafting of complicated devices of which thin-ness and small-ness is a fundamental attribute. As the technology of thin films progressed from optical to electronic applications, the definition of 'thin' moved from the 100 nm scale into the <10 nm domain where atomic scale effects start to become important design considerations. The opening of the 21st century brings us to a convergence of thin film deposition with atomic scale engineering. Atomic layer deposition is aimed at nanoscale process control. Self-assembled monolayers provide surfaces with unique and useful properties. Microelectronic mechanical sensors require a broad spectrum of nanoscale engineered materials all based on thin film techniques. Approaching device applications from the opposite direction of

the thickness scale, will challenge the thin film technologist to develop new methods to control the process and achieve practicality. The shift from inorganic to organic electronic materials is predicted to continue with concomitant changes in process technology. With microelectronics now reaching fundamental limits of miniaturization, thin film technologists will be forced to return to their beginnings, optical device technology, be it this time on a scale and with a required degree of control that was unthinkable in the last century.

### Tuesday Afternoon, October 3, 2000

### Thin Films Room 203 - Session TF-TuA

### Mechanical Properties of Thin Films Moderator: B. Starks, Veeco-CVC

#### 2:00pm TF-TuA1 The Nanomechanical Properties of Thin Films, J.E. Houston, Sandia National Laboratories. INVITED

Material properties and processes can appear remarkably different when viewed at the nanometer level. Mechanically, solids can approach the behavior of perfect single-crystals and inter-particle interactions become dominated by surface energetics and dyna mics. In thin films with nanometer scale grains, dislocation-loop formation can become unfavorable and grain sliding can become the dominant mechanism for plastic deformation. The study of the mechanical properties of these materials is presently enjoying increasing attention due in large part to the rapid development of scanning-probe techniques capable of making measurements on individual grains down to the nanometer level. In this presentation, I will illustrate some of these unique nanoscale effects in various applications of the Interfacial Force Microscope (IFM) to studies of the nanomechanical properties of thin films. The IFM is a scanning forceprobe microscopy similar to the Atomic Force Microscope but distinguished by its use of a mechanically stable, zero compliance force sensor. Used in a nanoindenter mode, this sensor offers accurate control of the probesample separation and provides a quantitative measure of the film's mechanical behavior. I will illustrate the IFM's unique capabilities w i th examples of near theoretical yield strength for single-crystal surfaces and the effect of surface steps on the strength. In polycrystalline films, I contrast the mechanical behavior as a function of grain size and film thickness and discuss the mechanisms responsible for the interesting observations. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

### 2:40pm TF-TuA3 Anomalous Plastic and Elastic Behaviors of Sputterdeposited TiN with 10 or 20 Inserted Thin Al Layers Evaluated by Nanoindentation, E. Kusano, N. Kikuchi, K. Tsuda, H. Nanto, A. Kinbara, Kanazawa Institute of Technology, Japan

The hardness enhancement observed for multilayered thin films results from the specialized mechanical properties of the interface region. In this paper, effects of thin Al layers inserted into the TiN matrix thin film on mechanical properties of the coating have been investigated in order to discuss a role of the interface regions made by the Al thin layer insertion. Thin films of TiN with AI thin layers have been deposited by dc magnetron sputtering. The total TiN thickness was kept at 500 nm for all prepared samples. The number of thin Al layers inserted was varied from 2 to 20 for the total Al thickness of 100 to 500 nm. The top layer of the coating was TiN for all sample coatings. Film hardness of prepared samples was estimated by nanoindentation. From a load-unload curve of the nanoindentation, energies consumed to induce plastic deformation and elastic deformation were estimated. A hardness of thin films with 20 Al layers decreased from 11 GPa to 8GPa when the total Al layer thickness increased from 100 to 500 nm. For a constant total Al laver thickness, the film with 20 Al layers yielded higher hardnesses. The film with 20 Al layers with a layer thickness of 5 nm was harder than the monolithic TiN film. While the energy used for plastic deformation during nanoindentation increased with the total AI layer thickness, the energy used for elastic deformation remained constant. Further, the dissipated energy decreased with increasing the number of Al layers inserted. These results obtained by nanoindentation measurement imply that the film becomes more elastic with increasing the number of Al layers inserted. A high microhardness obtained for a film with Al layer thickness of 5nm emphasizes a unique effect of thin Al layers or interface regions on mechanical properties of the coating.

#### 3:00pm TF-TuA4 Tungsten Silicide (WSi2) for the Alternate Gate Metal in Metal-Oxide-Semiconductor (MOS) Devices, K. Roh, S. Youn, S. Yang, Y. Roh, Sungkyunkwan University, Korea

Recently, it has been recognized that both achieving low gate resistance and suppressing poly-Si gate depletion are key factors for developing deep submicron MOSFETs. In the present work, tungsten silicide (WSi2) deposited directly on SiO2 is proposed for the alternate gate electrode for deep-submicron MOSFETs. PMOS capacitors were fabricated on 4~7@ohm@-cm, (100) n-type Si wafers. Thermal oxidation of the Si was carried out at 850°C for 80 s using RTP to grow ~110Å SiO2. WSi2 were then deposited directly on SiO2 in a cold-wall LPCVD system: Deposition temperature and pressure were 350°C and 0.7Torr, respectively. The ratio of SiH4/WF6 flow was changed from 40 to 70. RTP was used for postdeposition annealing at various conditions. Detailed analysis of mechanical properties of WSi2 deposited on SiO2 reveals that a low resistivity can be obtained while satisfying the requirement for the low thermal budget. In addition, HTEM results showed that WSi2-SiO2 interface remains very flat after annealing as-deposited WSi2 films using RTP at 780°C in vacuum. Since F diffusion into SiO2 during the WSi2 deposition and annealing steps has been known to cause the irregular formation of WSi2-SiO2 interface, we attribute the current results to the indirect evidence of negligible F diffusion. In addition, the electrical characteristics of annealed WSi2-SiO2-Si (MOS) capacitors were also improved in view of charge trapping. For example, oxide charging curves monitorted during Fowler-Nordheim tunnel electron injection indicate that the shift of flatband voltage is less for RTP annealed samples as compared to that of as-deposited samples. The phenomenon of gate depletion which has been a serious problem of poly-Si gate is also suppressed in the WSi2 gated MOS capacitors. The C-V data shifted to the positive gate bias after annealing, and we interpret that this positive shift is caused by the workfunction difference that may be caused by the change of Si to W ratio due to the annealing process.

# 3:20pm TF-TuA5 Structural and Mechanical Properties of TiC/Ti and TiC/B@sub 4@C Multilayers Deposited by Pulsed Laser Deposition, A.R. Phani, J.E. Krzanowski, University of New Hampshire; J.J. Nainaparampil, Systran, Inc.

Multilayer thin films have been shown to enhance the hardness as well as toughness of hard ceramic coatings, and the results often depend on the type of interlayer used. In the present study, we have investigated multilayers of TiC/Ti (for toughness enhancement) and TiC/B@sub 4@C (for hardness enhancement). Films were deposited on 440C steel and silicon substrates by pulsed laser deposition (PLD). Ti, B@sub 4@C and TiC targets were ablated in a background gas of 1mTorr Ar at substrate temperatures of 200, 400 and 600C. Samples were deposited having modulation periods ranging from 2.5 to 50 nm. Films were analyzed using nano-indentation hardness, x-ray diffraction, XPS and electron microscopy. Surface morphology and roughness of the samples were measured by scanning electron microscopy and atomic force microscopy, respectively. Tribological studies have also been conducted to evaluate the friction and wear properties of these films. Films with low modulation periods showed lower residual stresses as measured by x-ray diffraction methods. The nano-indentation hardness of compositionally modulated Ti/TiC and TiC/B@sub 4@C multilayer films were found to be dependent on composition modulation frequency. TiC/Ti films showed reasonably high hardness values (37GPa) for the lower period samples despite the incorporation of the metal layer, and TiC/B@sub 4@C films showed hardness levels up to 42GPa. Film composition depth profiles performed by using XPS showed 1-2 at % oxygen in the deposited films, as well confirming the presence of composition modulations. The mechanisms of hardness enhancement and its relation to tribological properties will also be discussed.

3:40pm **TF-TuA6 Structural Studies of AIN Thin Films during Low Temperature RF Sputter Deposition**, *F. Engelmark*, *G.F. Iriarte*, *I.V. Katardjiev*, *M. Ottosson*, University of Uppsala, Sweden; *P. Muralt*, Laboratiore de Ceramique, Switzerland; *S. Berg*, University of Uppsala, Sweden

AIN is a material used in a wide variety of applications such as electroacoustic devices, blue diodes, IR-windows, thermal conductors, MISstructures, IC-packaging, etc. Thin piezoelectric AIN polycrystalline films have been grown on Si and SiO@sub 2@ using RF magnetron sputter deposition in an Ar/N@sub 2@ gas mixture. The structural properties of the films have been optimized by varying the deposition parameters, such as process pressure, gas mixture, substrate temperature, discharge power, etc. It was found that the best film texture was obtained for a particular set of parameters, namely process pressure of 8 mTorr, substrate temperature 350°C, discharge power 350W and a gas mixture of 25%Ar and 75%N@sub 2@. The films as examined by XRD exhibited a columnar structure with a strong (002) texture, and a FWHM rocking curve of 1.6 degrees. A crystallite size of 38 nm was calculated using Sherrers formula. AFM measurements indicated a surface roughness with an rms value of 8 Å. Classical nonapodized transversal SAW filters operating at a frequency of 534 MHz were fabricated to estimate the electro-acoustic properties of the films. The measurements indicated a coupling coefficient of 0.46% and a phase velocity of 4900 m/s. Further, thin epitaxial films were grown on

### Tuesday Afternoon, October 3, 2000

alfa-Al@sub 2@O@sub 3@(001) under the same deposition conditions. The films exhibited a (001)AIN//(001)alfa-Al@sub 2@O@sub 3@ plane orientation with a (002) rocking curve FWHM value of about 0.4 degrees, indicating a relatively good alignment of the c-axis or a low dislocation density. The in-plane orientation was [110]AIN//[120]alfa-Al@sub 2@O@sub 3@ corresponding to a rotation of the AIN film of 30 degrees with respect to the alfa-Al@sub 2@O@sub 3@(001) surface. Cross-sectional TEM studies indicated a population of both thread and edge dislocations with decreasing concentrations with film thickness.

### 4:00pm TF-TuA7 Multifunctional Ceramic Films, C.R. Aita, University of Wisconsin, Milwaukee INVITED

The concept of a film that can perform different functions as required by changing external stimuli has long intrigued scientists and engineers. The nanostructure revolution has made possible new uses for ceramic films that behave as multifunctional "smart" materials. In this paper, we first review new developments in traditional uses for multifunctional films, such as those involving electrochromic and thermochromic materials. Next, we describe new uses for multifunctional ceramic films. The design and development of a biocompatible coating that protects blood-interfacing implants against corrosion and mechanical degradation is used as an example of the challenges that face synthesis and characterization of these multifuctional "smart" materials.

#### 4:40pm TF-TuA9 Quantification of Scratch Resistance and Accelerated Wear for Thin Film Coatings Using the Newly Developed Micro-Tribometer and Testing Procedure, *C. Gao*, *N. Gitis*, Center for Tribology

Quantification of scratch and accelerated wear resistance of thin films ranging from 1 nm to 1000 nm was achieved by using critical loads, at which the given films were progressively worn through. Progressive worn through of thin carbon films (3 nm to 8 nm) on magnetic disks using a micro-blade under precision motion with linearly increasing loads from 0.2 grams up to 400 grams was clearly observed simultaneously from electrical contact resistance (ECR), friction force and acoustic emission (AE) signals. At the critical load, friction force and AE fluctuated violently and ECR dropped to practically zero. The critical load was found to increase with increasing carbon thickness, as expected. The wear depths at the critical loads were measured post-test using Tencor profiler and optical surface reflection and found to be in excellent agreement with film thickness. A lubricant film as thin as 1 nm on the carbon films enhanced the critical load by a factor of five to ten. The same testing procedure was applied for thicker diamond-like carbon films on silicon substrate ranging from 50 nm up to 1000 nm, but with linearly increasing loading force from 0.2 N up to 40 N. Good correlation was found between critical load and film thickness, and also between critical load and residue film stress also. However, there was no correlation between critical load and nano-hardness. We believe that the nanohardness measurements may not apply for films thinner the sub-micrometer, since the contact stress distributed well into the substrate when nano indentation was made. The successful quantification of scratch resistance and accelerated wear is attributed to precision motion, linearly increasing load mechanism and the contact geometry of the micro-blade. The micro-blade will be described and the mechanism for its effectiveness on surface film evaluations will be discussed, as compared to much less effective counter surfaces, such as a diamond stylus or a stainless steel ball.

## 5:00pm TF-TuA10 Lubricating Characteristics of Zinc Oxide: Effect of Carbon, Silicon and Boron as Additives, J.J. Nainaparampil, Systran Federal/Air Force Research Lab; J.S. Zabinski, Air Force Research Lab

Zinc Oxide, with its wurzite structure, is a unique material that exhibits lubricious qualities and desirable electronic and optical characteristics. There have been numerous studies on the doped zinc oxide thin films profiling it as an optical coating material or as a semiconductor material. But no significant amount of work has been reported yet on this material as a tribological material. Recent work of this lab revealed some of the tribological potentials of this material. Due to its open nature and desirable coordination number, zinc can move around different lattice positions and be substituted with external atoms to become interstitials. Zinc oxide shares the hexagonal structure, which is commonly seen in most of the widely used solid lubricants. The open nature of its crystal structure and similarity of this structure with that of the widely used solid lubricants are quite desirable qualities. To preserve these qualities, and to manipulate the tribological characteristics, additives of ionic radii comparable that of Zn need to be selected. Alumina doped zinc oxide have already been studied and found to have low friction and good wear characteristics. In this work, properties of thin films of zinc oxide, formed with simultaneous addition of Si, C and B will be reported. Si added films showed low friction and long

wear life above 350 Å<sup>Q</sup>C. Deposition direction and oxygen working pressure also had a profound effect on these films. Results of common surface analyzing techniques like XPS, SEM, AFM, and XRD, Raman, Nanoindentation and Friction and Wear will be reported.

### Thin Films

Room Exhibit Hall C & D - Session TF-TuP

#### **Poster Session**

#### TF-TuP1 Influence of Annealing Temperature on Simultaneous Vapor Deposited Calcium Phosphate Thin Films, *M. Hamdi*, *A.M. Ektessabi*, Kyoto University, Japan

Calcium phosphate is an important bioceramic with tremendous potential for biomedical applications. Its unique bioactivity promotes rapid bone growth and strong interfacial fixation that has particular benefit to orthopedic and dental applications. The effect of different annealing temperature on the characteristics of thin film calcium phosphate coatings fabricated by a novel simultaneous vapor deposition method was investigated. Heat treating the as-deposited films was necessary to change the amorphous coating to a crystalline coating. The films were annealed for 3 h at 400, 700, 1000 and 1200°C in air. After annealing, the structure and the chemical composition of these films were characterized with incident light microscopy, rutherford backscattering spectroscopy and x-ray diffraction. Scratch test was conducted to measure the adhesion strength of the coatings to the substrate. Results showed that after annealing at 1000°C, crystalline hydroxyapatite appeared to co-exist with tricalcium phosphate phase. The surface roughness increased with increasing annealing temperature. The adhesion of the coatings was highly affected by the annealing temperature. From the results, it can be suggested that 1000-1200°C is probably the best annealing temperature range for calcium phosphate coatings produced by simultaneous vapor deposition method.

#### TF-TuP3 Formation and Evolution of Photoluminescence Si-based Nanostructured Thin Films Prepared by Laser Ablation, *A. Kabashin, M. Meunier,* Ecole Polytechnique de Montreal, Canada; *R. Leonelli,* University of Montreal, Canada

A method of Pulsed Laser Ablation (PLA) from a Si target in an inert He ambient has been applied in combination with different post-deposition oxidation procedures for the fabrication of Si/SiOx nanostructured films on Si substrates. The films exhibited strong visible photoluminescence (PL), which remained stable even under a prolonged continuous irradiation of the sample by an excitation laser light. The peak energy of the PL spectra could be finely varied between 1.58 and 2.15 eV by a change in the residual gas pressure during the deposition process. An effect of thermal annealing on the PL properties of the Si/SiOx films has been examined and compared with the results for Si-based films produced by thermal evaporation from a Si target in vacuum. For both deposition techniques, the thermal annealing led to a dramatic change of PL properties giving rise to a fixed PL peak around 2.2 eV. Photoluminescent properties of particles formed by PLA with natural oxidation were different than those of thermally oxidized amorphous Si films. In addition, the PL properties of the as-deposited films were found to be sensitive to surface chemistry reactions. A change of storage ambient and oxidation conditions could lead to significant changes of positions and intensities of PL peaks. Possible mechanisms of formation and evolution of PL are considered.

TF-TuP4 Deposition of Device Quality Amorphous Silicon, a-Si:H, Thin Films by the Hollow Cathode Plasma-Jet Reactive Sputtering System, Z. Hubicka, R.J. Soukup, G.K. Pribil, N.J. Ianno, University of Nebraska, Lincoln Device quality hydrogenated amorphous silicon, a-Si:H, thin films have been deposited by means of a dc hollow cathode plasma jet with magnetic field confinement. Single crystal silicon nozzles have been reactively sputtered in the high density hollow cathode discharge. Only nontoxic gases argon and hydrogen have been used for this purpose. Different configurations of the dc hollow cathode have been used for the deposition process. Device quality a-Si:H thin films have been achieved with light to dark conductivity ratios >10@super 6@ and with the light conductivity near 10@super -5@ S and dark conductivity between 10@super -11@ and 10@super -12@ S. This was accomplished with a specific configuration of the hollow cathode discharge in the silicon nozzle. Our best films have a Tauc-band gap near 1.8 eV and an atomic hydrogen concentration of about 14%. The growth rate achieved for device quality a-Si:H films was in the range of 2 to 3  $\mu$ m/h.

TF-TuP5 Influence of Bias Voltages on the Oxygen Diffusion Behaviour in dc Magnetron Sputtered In/Sn Films, M. Quaas, H. Wulff, H. Steffen, R. Hippler, University of Greifswald, Germany

Thin metallic In/Sn films were deposited on unheated Si(100) wafers by means of dc planar magnetron sputtering at different negative substrate voltages. The In/Sn x-ray reflection line profiles of these films are broadened. The broadened profiles can be considered as an indicator of decreasing lattice perfection in the as-deposited films. To study the influence of the different microstructures on the oxygen diffusion behaviour these films were annealed in a vacuum chamber mounted on a theta-theta-diffractometer. Using in-situ high-temperature grazing incidence x-ray diffractometry (GIXRD) the growth of crystalline indium-tinoxide (ITO) layers was observed. From the time dependence of the ITO(222) peak intensity conclusions on the reaction kinetics can be drawn. An analytical model was developed for the investigation of the diffusion process by means of the x-ray integral intensity. From this model the effective diffusion coefficients D were determined for films deposited at different substrate voltages. The correllation between the film microstructure and the variing diffusion coefficients is discussed.

#### TF-TuP6 Study on Indium Nitride Films Deposited by DC Magnetron Sputtering, *P.K. Song*, *D. Sato*, *N. Ito*, *Y. Shigesato*, Aoyama Gakuin University, Japan

The III-V nitride semiconductors with a wurtzite structure such as aluminum nitride (AIN), gallium nitride (GaN), indium nitride (InN), have been investigated for various applications including optoelectronic devices because they have direct energy band gaps corresponding to wide wavelengths from the red to the ultraviolet. However, InN has received little attention compared with AIN or GaN, because its poor thermal stability and difficulties in depositions. In this study, InN films were successfully deposited on soda-lime glass at the substrate temperature T@sub s@=RT-400ï½°C by dc reactive magnetron sputtering using In metal target under various total gas pressure (P@sub tot@=0.5-3.0Pa) of mixture gases of Ar and N@sub 2@. Crystal structure and surface morphology of the films were investigated by X-ray diffraction (XRD) and atomic force microscope (AFM). Without substrate heating, a clear InN (002) XRD peak was observed for the films deposited at 0.5-3.0 Pa with N@sub 2@ gas flow ratio higher than 60%. With increasing P@sub tot@ from 0.5 to 3.0 Pa, degradation in the crystallinity of the films was clearly observed. Based on these results, two possible mechanisms are postulated. One is that the chemically active species generate by electron-impact dissociation of N@sub 2@ molecules could be increased with the decreasing P@sub tot@ and increasing electron temperature, which should result in the enhancement of the crystallization during reactive film growth. Another mechanism is that the crystallinity of the film is affected by the kinetic energy of sputtered In atoms arriving at substrate surface which could enhance surface migration of the In atoms and hence the crystallinity. The effects of increasing T@sub s@ on the film structure will also be discussed in detail.

#### TF-TuP7 The Effect of Heat-treatment on the Structural and Mechanical Properties of MoS@sub 2@/Ti Composite Coatings, B.J. Kim, J.H. Dautzenberg, Eindhoven University of Technology, The Netherlands

MoS@sub 2@/Ti composite coatings have been coated on stainless steel by dc magnetron sputtering. After deposition, MoS@sub 2@/Ti coatings were heat-treated in vacuum in order to investigate the effect of heat treatment on the mechanical properties of the coating. Before and after heat treatment, the structure and concentration of co-sputtered MoS@sub 2@/Ti coating were analyzed by x-ray diffraction method, energy disperse spectroscopy, as well as x-ray photoelectron spectroscopy. The mechanical properties of the coatings such as hardness, elastic modulus, residual stress, and critical fracture strain of bending, were also measured by nanoindentation method, thin foil method, and bending test with electrochemical detection. Ti addition to MoS@sub 2@ coating prohibits the micro- or macro-crystallized structure of the coating, and MoS@sub 2@/Ti coating makes a single-phase solid solution structure up to 20 at% Ti. Mechanical properties of coating are dependent on Ti concentration. The hardness and elastic modulus of MoS@sub 2@/Ti composite coatings increased as increasing Ti concentration. The residual stresses of MoS@sub 2@/Ti composite coatings dramatically increased by adding Ti to MoS@sub 2@ coating. MoS@sub 2@/Ti composite coatings were micro- or macrocrystallized if the heat treatment temperature was higher than 500°C. It resulted in the increase of porosity and decrease of hardness of the coating. The concentration of sulfur abruptly decreased, if the heat treatment temperature is higher than 750°C.

TF-TuP8 Supermagnetron Plasma CVD and Qualitative Analysis of Electrical Conductive Hard Carbon (DLC) Films, *H. Kinoshita*, *M. Yoshida*, Shizuoka University, Japan

Using a supermagnetron plasma chemical vapor deposition (CVD) method, electrical conductive diamond-like carbon (DLC) films were formed.@footnote 1@ The electrical conductive DLC films were suited for the formation of high performance field emitters, which were formed by coating Si tips with them. In the formation of DLC films on Si and glass wafers, i-C@sub 4@H@sub 10@/N@sub 2@ mixed gases were introduced into the discharge chamber. Deposition rate, hardness and resistivity were measured as a function of N@sub 2@ concentration, total gas pressure, rf powers or temperature of lower-electrode on which a wafer was put. With increase of N@sub 2@ concentration (up to 70%), rf powers and lowerelectrode temperature, the film resisitivity was decreased. And also with decrease of total gas pressure, the film resisitivity was decreased. FT-IR spectroscopy measurements revealed that the increase in electrical conductivity could be attributed to CN single and triple bonds creation in DLC films. The lowest resistivity of 0.034 @ohm@ cm was achieved at the N@sub 2@ concentration of 65%, total gas pressure of 30mTorr, upperand lower-electrode rf powers of 1kW/1kW, and lower-electrode temperature of 100 °C. @FootnoteText@@footnote 1@H.Kinoshita and A.Yamauchi, J.Vac.Sci.Technol.A 14, 1933 (1996).

### TF-TuP9 Deposition of W Films using Different Underlayers, L.V. Kozlovsky, A. Antinsh, V. Pashkevich, University of Daugavpils, Latvia

It is known that the formation of beta-Ta crystalline phase in sputtered Ta films depends on the nature of the substrate or underlayer. Comparison of our data as well as of results of various authors reveals the correlation between beta-Ta formation in Ta/Me bilayers and mismatching of the shortest interatomic distances (SID) in bcc Ta and in Me. Beta-Ta phase presents in the Ta films when SID mismatching greater of 9%. The aim of the present work was to determine whether beta-W formation in W/Me bilayers occurs at such conditions. We deposited 100 nm Me/X nm W (Me: Nb,Al, Fe, Zr, Hf, Dy ; X = 20,50, 100, 200 nm) bilayers on near roomtemperature glass substrates in a Xe discharge at a pressure of (7 - 9) x10@super -4@ Torr using Penning discharge sputtering devices. The base pressure was nearly 5x10@super -9@ Torr.10 nm C underlayer was deposited on substrates at the same vacuum conditions before bilayers deposition. The structure of the films was investigated by X-ray diffraction (XRD). In the case of Nb and Al the SID mismatching is less of 4% but for other metals it is in the interval (10 - 28)%. Wolfram layers structure was characterized as bcc W. XRD profiles for all bilayers had no peaks corresponding to beta-W. W films on Nb and Fe had texture (110). Preferred orientation of {110} and {211} planes parallel to the substrate plane was found in W layers in the case of Al, Zr, Hf, Dy underlayers. The results of present work have shown that beta-W formation in Me/W bilayers is not dependent on underlayer. Data of the bilayers crystal structure investigations will be presented and discussed.

### **TF-TuP10 Energetic Oxygen Ions in the Reactive Sputtering of Zr Target in Ar+O@sub 2@ Atmosphere**, *K. Tominaga*, **T. Kikuma**, University of Tokushima, Japan

In the sputtering of Zr target in Ar+O@sub 2@ atmosphere, ZrO@sub 2@ films are deposited. However, sometimes anomalous phenomena that the films are easily peeled from the substrate or degraded. These seems to be due to the presence of the energetic oxygen ions which are generated in the sputtering. Therefore it becomes important to know the extent of the flux of energetic oxygen ions. We constructed a probe to estimate the flux of energetic oxygen ions and applied it to the observation of the energetic oxygen intensity from the sputtered Zr atoms, monitoring the target surface oxidization. The results show that the Zr target is very active in oxygen atmosphere and oxydized fully with a small oxygen partial pressure. The flux of energetic oxygen ions for Zr target is 2 or 3 times stronger than that for Zn target.

### TF-TuP11 Low Temperature Crystallization of TiO@sub 2@ Thin Films Sputter-deposited in Ar-H@sub 2@O Plasma, T. Ohwaki, Y. Taga, TOYOTA Central R&D Labs., Inc., Japan

Polycrystalline TiO@sub 2@ thin films are widely used as photocatalytic materials. Low temperature crystallization of the films is one of the important techniques for realizing wide spread application. We studied low temperature process for preparing TiO@sub 2@ thin films by sputtering. We found that the TiO@sub 2@ thin films deposited by reactive

magnetron sputtering of Argon-water plasma were crystallized to anatase poly-crystal by post-annealing at only 200°C in air, while TiO@sub 2@ thin films sputter-deposited by Argon-oxygen plasma were crystallized at above 500°C post-annealing. To clarify the mechanism of low temperature crystallization, we investigated the structure of TiO@sub 2@ thin films sputter-deposited by Ar-D@sub 2@O or Ar-O@sub 2@ plasma by means of Infrared-Reflection Absorption Spectroscopy (IR-RAS). The detailed analyses of the absorption bands revealed an existence of hydroxyl groups in TiO@sub 2@ thin films sputter-deposited by Ar-D@sub 2@O plasma and relaxation of the lattice. This result suggests that the introduced hydroxyl groups cut the amorphous network structure of the TiO@sub 2@ thin films, which enhances the rearrangement of the atoms in the films by postannealing.

### TF-TuP12 Selective Growth of TiO@sub 2@ Thin Films on Si(100) Surfaces by Combination of MOCVD and Microcontact Printing Method, B.-C. Kang, J.-H. Lee, H.-Y. Chae, D.-Y. Jung, S.-B. Lee, J.-H. Boo, Sungkyunkwan University, Korea

Patterning of TiO@sub 2@ thin films was successfully performed by MOCVD onto Si (100) substrates of which surface were modified by an organic thin film. The organic thin film of self-assembled monolayer (SAM) was in first obtained by the micro-contact printing ( $\mu$ m-CP) method. Selective deposition of TiO@sub 2@ thin film with 1500 Å thickness has then been carried out onto those surfaces at the temperature in the range of 300 to 500 °C by MOCVD without any carrier and bubbler gas. AES and XRD analysis showed that deposited TiO@sub 2@ thin film has a stoichiometric composition in the depth and polycrystalline anatase phase. @alpha@-step profile and optical microscopic images also showed that the boundaries between OTS SAMs areas and selectively deposited TiO@sub 2@ thin film areas are very definite and sharp. Capacitance-voltage measurement made on a TiO@sub 2@ thin film gave a dielectric constant of 21, suggesting a possibility of electronic materials applications.

### TF-TuP13 Oxidation Kinetics of the Growth of Thin Alumina formed by Plasma Oxidation, A. Quade, H. Wulff, University of Greifswald, Germany

Plasma treatment is an original way to modify the surface of metals and to improve their properties for an application in industry. In our study thin Al films were plasma oxidized using a 2.45 GHz slot antenna microwave plasma source (SLAN) at different types of chemical reactive and nonreactive plasma species to form thin aluminium oxide films. To determine the activation energy for plasma oxidation process investigations at different substrate temperatures were performed. For the characterization of the Al and the developed oxide grazing incidence x-ray reflectometry (GIXR), grazing incidence x-ray diffractometry (GIXRD), Fourier-Transform infrared spectroscopy (FT-IR) and x-ray photoelectron spectroscopy (XPS) were used. Because the formed alumina is x-ray amorphous, the integral intensity of Al(111) peak of the non-reacted Al film was determined timecontrolled for the quantification of the developed oxide. Together with the total thickness of the layer these values allow the calculation of significant kinetic parameters. The alumina film growth is controlled by two rival processes, a diffusion process and a sputter process. The growth kinetics depends on plasma type, concentration of activated oxygen species and temperature.

### TF-TuP14 Epitaxial Growth of CeO@sub 2@ Film on YSZ Buffered Si (111) Substrates, J.H. Yang, K.W. Lee, J.W. Seo, C.Y. Park, Sungkyunkwan University, Korea

We have grown cerium dioxide (CeO@sub 2@) films as an insulating layer for silicon-on-insulator (SOI) structure. When CeO@sub 2@ was deposited on Si (111) substrate up to 620 by using electron beam evaporator (ANELVA VI-43N), at the interface between CeO@sub 2@ film and Si (111) substrates, the SiO@sub 2@ layer was observed which is in agreement with earlier report.@footnote 1@ The structure of CeO@sub 2@ films on Si (111) substrate was formed to be columnar. We observed that the columnar structure of CeO@sub 2@ films and SiO@sub 2@ formation disturbed the epitaxial growth of the Si film on top layer. Hence, we have deposited YSZ as a buffer layer on the Si (111) substrate and grown CeO@sub 2@ film. We analyzed YSZ and CeO@sub 2@ films by XRD, HRTEM and AFM. We found that deposition of YSZ on Si (111) prohibits the growth of SiO@sub 2@ layer. The morphology of CeO@sub 2@ film on YSZ buffered substrates was improved as compare with the morphology of CeO@sub 2@ film with not YSZ buffered substrates. @FootnoteText@ @footnote 1@C.G. Kim et al, J. Kor. Phys. Soc., 32, 64(1998).

**TF-TuP15** The Effect of Annealing on the Electroless Plated Cu Metallization for Sub-micron Interconnection, *J.H. Lin*, National Tsing Hua University, Taiwan, Taiwan, ROC; *T.L. Lee*, National Chiao Tung University, Taiwan, TAIWAN, ROC; *Y.Y. Tsai*, National Tsing Hua University, Taiwan, TAIWAN, ROC; *X.W. Liu*, National Tsing Hua University, Taiwan, Taiwan,ROC; *C.C. Lin*, National Chiao Tung University, Taiwan, TAIWAN, ROC; *H.C. Shih*, National Tsing Hua University, Taiwan, ROC

Both patterned and blank wafers are carried out using Pd as catalyst by plasma immersion ion implantation (PIII) after which Cu is electroless plated. The characteristics of electroless plated copper specimens after annealing in the 95% nitrogen + 5% hydrogen ambient atmosphere with an annealing temperature from 150 to 700 for 1 hour are investigated by sheet resistance, surface roughness, crystallographic texture, cross-section morphology, film hardness, adhesion strength and microstructure. The sheet resistivity of Cu film decreases from 3.8 to 3.3  $\mu$  \*-cm after annealing at the temperature from 150 to 700. AFM shows that the surface became rougher as the annealing temperature getting higher. HRTEM images show that, the Pd implantation layer of the as-received specimen is an amorphous structure and crystallized after the annealing treatment. If the annealing temperature is higher than 300, the copper reflow effect in via or trench is very clear. Therefore, the post electroless copper annealing at about 300 stabilizes the copper microstructure and completes interconnect metallization performance.

TF-TuP16 SrBi@sub 2@Ta@sub 2@O@sub 9@ Ferroelectric Films Deposited by PLD Under Different Annealing Conditions, M.P. Cruz, Centro de Investigacion y de Estudios Superiores de Ensenada, México; J.J. Portelles, Universidad de La Habana, Cuba; J.M. Siqueiros, UNAM, México

A new step in the deposition process of SrBi@sub 2@Ta@sub 2@O@sub 9@ (SBT) films is introduced to avoid short circuits in the electrodeferroelectric-electrode capacitor due to microcracks in the SBT material. Here, the SrBi@sub 2@Ta@sub 2@O@sub 9@ films, deposited on Pt/TiO@sub 2@/SiO@sub 2@/Si substrates by PLD, were grown in a twostep process, each with its corresponding annealing treatment, in such a way that the second deposit fills the cracks of the first layer preventing the percolation of the electrode material from the top to the bottom electrode. SEM, TEM, XRD and AES techniques were used to characterize the films. Xray analysis showed a BiO@sub 2@ crystalline phase for low deposition and annealing temperatures and its transformation into polycrystalline SBT as those temperatures increased. After Pt top electrodes were deposited on the SBT films, the micro structural results obtained with the abovementioned techniques, were correlated to the ferroelectric properties observing an increase in polarization values with processing temperature. DGAPA-UNAM, Proj. IN104000, CoNaCyT, Proj. 33856E. Thanks are due to E. Aparicio, P. Bartolo, J. Fernández, I. Gradilla, P. Ruiz and G. Vilchis.

#### TF-TuP17 Effect of Pulsing in Dual-mode Microwave/Radio Frequency Plasma on the Growth of SiN@sub 1.3@ Optical and Protective Coatings, *R. Vernhes, O. Zabeida, J.E. Klemberg-Sapieha, L. Martinu,* Ecole Polytechnique of Montreal, Canada

Plasma enhanced chemical vapor deposition (PECVD) is becoming increasingly attractive for the fabrication of optical films and coatings. The main reason is a possibility to obtain suitable optical, mechanical, permeation barrier and other functional characteristics when depositing on temperature-sensitive substrates such as polymers. In the present work, we deposited amorphous hydrogenated silicon nitride (SiN@sub 1.3@) in dual-mode microwave/radio frequency (MW/rf, 2.45 GHz / 13.56 MHz) discharge using a silane - ammonia mixture. We systematically studied the effect of MW and rf power modulation, namely the effect of pulsing frequency, duty cycle, and pulse synchronization on the optical (refractive index, extinction coefficient), mechanical (stress, microhardness, adhesion, etc.) and microstructural characteristics (concentration of hydrogen, chemical bonding, sutface morphology etc.). Using time- and mass-resolved ion energy analysis, we determined the effect of dissipated power and selfbias potential on the instantaneous ion energy distribution functions and on the energetics of the film growth. We found that, depending on rf matching, two distinct modes of operating the pulsed MW/rf discharge are possible, namely (i) when rf power is delivered during MW pulse, and (ii) when it is delivered between MW pulses. We discuss the possibilities to match in one design the optical and mechanical properties necessary to obtain enhanced film system stability for advanced optical and optoelectronic applications.

TF-TuP18 Synthesis of Cubic Boron Nitride Films on Ion Implanted Silicon Substrates, *Q. Li, Z.F. Zhou, I. Bello, C.S. Lee, S.T. Lee,* City University of Hong Kong, China

Cubic boron nitride (c-BN) films were prepared by radiofrequency (rf) magnetron sputtering of a hexagonal boron nitride (h-BN) target in Ar/N@sub2@ mixtures. The boron nitride films were deposited on chemically cleaned and in-situ presputtered silicon substrates. The substrates were implanted by boron, nitrogen and nickel ions and their combinations. During deposition, the substrates were pulsed biased and heated to 600 °C. The synthesized c-BN films showed good adherence to the substrate and exhibited phase purity over 90 % as determined by fourier transform infrared spectroscopy (FTIR). Atomic scale analysis, using high resolution transmission electron microscopy (HRTEM), showed nanocrystalline boron nitride structure. Cubic boron nitride phase grew both on the silicon substrates directly and the top of transition h-BN layers. The presented c-BN synthesis reduced the film stress as indicated by the beam bending technique and shift of the absorption peak of TO mode in FTIR spectra. The implanted species acted as active sites for film/substrate interfacial reaction and contributed to the stress reduction. The experimental results showed that the film stress was tailored by the presented novel method established on interfacial engineering which in return yielded high quality c-BN films.

TF-TuP19 Preparation and Characterization of Amorphous CN@sub x@ Thin Films by Pulsed Laser Deposition, Y. Aoi, K. Ono, K. Sakurada, E. Kamijo, Ryukoku University, Japan; M. Sasaki, K. Sakayama, Industrial Research Center of Shiga Prefecture, Japan

Compounds in carbon-nitrogen system are interesting because they exhibit unique properties such as high value of hardness, low friction coefficient, chemical inertness, and variable elctronic and optical properties. In this paper, amorphous carbon nitride (a-CN@sub x@) thin films were deposited on a Si substrate by pulsed laser deposition (PLD) by use of graphite target under various deposition conditions. We have investigated the bonding structure of deposited films. Structural changes by heat treatment were also investigated. The PLD system used in this study consists of a KrF excimer laser, nitrogen radical beam source, and vacum chamber. The laser beam was focused onto a rotating graphite target surface to give various energy density. Deposition was carried out in N@sub 2@ atmosphere, in Nitrogen plasma, and under irradiation of nitrogen radical beam. Heat treatment of films were carried out following to the deposition in the vacuum chamber. The films were charactereized by XPS. FT-IR. Raman spectroscopy, and TEM observation. The maximum N/C ratio of the deposited film was 0.24 in the present experimental conditions. N 1s electron spectra of deposited films indicated the nitrogen atoms in the film were mainly bonded to sp@super 2@ and sp@super 3@ hybridized carbon atoms. FT-IR and Raman spectra indicated that N-spC are small as compared with N-sp@super 2@C and N-sp@super 3@C. The fraction of Nsp@super 3@C increased with increasing N/C ratio in the deposited film. The heat treatment induced a nitrogen loss and graphitization of the film. It was found that nitrogen atoms bonded to sp@super 3@C are preferentially eliminated by heat treatment.

### TF-TuP20 Sputtered Aluminum Nitride Thin Films for Bulk Acoustic Wave Resonators, R.N. Tait, Carleton University, Canada

Thin film bulk acoustic resonators formed by sputter deposition of piezoelectric films of aluminum nitride on silicon substrates offer an attractive approach to monolithic integration of high Q passive circuit elements with active devices. Such resonators could provide low cost, high performance filters for the steadily growing numbers of consumer wireless communication devices. Fabrication of these resonators requires a well characterized low temperature deposition process for aluminum nitride. This material has been studied for use in sensors and actuators, as well as acoustic wave devices. Radio frequency reactive magnetron sputtering produces high quality films. The deposition rate is too slow to be practical for many applications, however for high frequency resonators operating above 1 GHz the film thickness and deposition time is more reasonable. This work describes aluminum nitride films deposited by radio frequency reactive magnetron sputtering, using a Box-Behnken experimental design. Factors included power from 2 to 6 W/cm@super 2@, pressure from 1 to 1.6 Pa, and N@sub 2@ flow from 50% to 100% of the total flow. Measured results include X-ray diffraction spectra and measurements of piezoelectric coefficients. X-ray diffraction measurements indicate highly (002) c-axis oriented films. Piezoelectric coefficients were measured by depositing aluminum nitride capacitors on silicon beams and measuring charge generation as each beam was deflected a known distance. These results

provide parameters for films that enable accurate modeling and design of high frequency thin film bulk acoustic wave resonators.

TF-TuP21 Monochromatized Light Emitter using Si Doped Glass with Dielectric Multilayer Resonator, *T. Ichinohe*, Tokyo National College of Technology, Japan; *S. Nozaki, H. Morisaki*, The University of Electro-Communications, Japan; *S. Masaki*, Tokyo National College of Technology, Japan; *K. Kawasaki*, TDY Co. Ltd., Japan

Extensive studies have been made on nanometer sized Si ultrafine particle films (the Si nano-structured films) as a new functional thin film material applicable to Si based photo-electronic functional devices. Si-doped glass (Si-DG) films, especially, are expected because of the chemical stability and less aging degradation. However, they have wide bandwidth of luminescence spectral. To overcome the drawback for light emitter using Si-DG films, we fabricated a Fabry-Perot optical resonator with dielectric multilayer reflector. Both Si-DG films and multilayered reflectors were formed by the ion beam sputter-deposition (IBSD) technique. A conventional method to fabricate Si-DG films was the co-sputtering of a composite target, composed of Si chips placed on a SiO@sub 2@ target. The multilayer-reflecting mirror was fabricated by alternate sputtering of 5inch CeO@sub 2@ target and Si/SiO@sub 2@ composite one. The quarterwavelength optical thickness rule was used to design the multilayered reflector. To activate a Si-DG layer for a light emitter, the Si-DG film was heat-treated with about 900 °C. It was found that the heat-treatment was contributed to form Si nano particles with a diameter of about 3-4 nm estimated by TEM observation. The luminescent Si-DG film showed extremely broad PL spectra, the full width of half maximum (FWHM) being typically 1 eV. In order to improve the spectral distribution, the PL spectrum of Si-DG film with the optical cavity, which was sandwiched by metal (Ag) film and a dielectric multilayered reflector, reduced down about 0.1 eV, using a 20 paired CeO@sub 2@/Si-DG multilayer reflector. The application to EL device with the narrow band spectrum can be made by the improvement of contact electrode.

#### TF-TuP22 Measurement of Boron and Phosphorus Concentration in BPSG Thin Films Using FTIR and Artificial Neural Networks, *M.F. Tabet*, *W.A. McGahan*, Nanometrics Inc.

Borophosphosilicate glass (BPSG) thin films have been widely used in semiconductor device fabrication as interlayer dielectric films due to their excellent planarization, flow properties, and passivation barriers against moisture penetration. FTIR spectroscopy combined with chemometric techniques has been shown to accurately measure boron and phosphorus concentrations in BPSG thin films. A neural network is a set of simple, highly interconnected processing elements imitating the architecture of the human brain, which are capable of learning information presented to them. In this work Reflectometry measured at the same location as the FTIR is used to accurately measure film thickness. The thickness along with the FTIR data are then presented to a trained neural network which predicts the boron and phosphorus concentration in the film. Reflectance, FTIR and an independent measurement of concentration, XRF in this case. from a set of calibration wafers is required to train the neural network. Predicted concentrations from both calibration and test wafers were an average of 1 percent off XRF measurements. This measurement program was implemented on a Nanometrics NanoSpec 8000XSE, a standalone metrology tool, and will simultaneously measure thickness, index and both boron and phosphorus concentrations. This measurement can be easily transferred to the NanoSpec 9000, which is an integrated metrology tool. This measurement system is ultra-compact and was designed specifically for integration into semiconductor processing equipment. Integrated measurements of thickness, optical constants and dopent concentration would improve overall equipment effectiveness through advanced process control. This would provide process engineers immediate feedback and should reduce scrap and monitor wafers.

TF-TuP23 Investigation of the W-TiN Metal Gate for Metal-Oxide-Semiconductor Devices, S. Youn, K. Roh, S. Yang, Y. Roh, Sungkyunkwan University, Korea; Y.C. Jang, K.S. Kim, Sungkyunkwan University, Korea, South Korea; N.-E. Lee, Sungkyunkwan University, Korea

Several research groups recently proposed that W-TiN metal gate deposited on thin SiO2 may be suitable for the deep-submicron MOSFETs. Although the previous work demonstrates the promising results, the roles of TiN have not been systematically studied. We present experimental results in the present work that the change of Ar to N2 ratio during the TiN deposition by the reactive sputtering decides the crystallinity of LPCVD W, as well as the electrical properties of the W-TiN/SiO2/Si capacitor. In particular we show that the threshold voltage can be controlled via

changing the Ar to N2 ratio. MOS capacitors were fabricated on 4~7@ohm@-cm, (100) p-type Si wafers. Thermal oxidation of the Si was carried out at 850°C for 80 s using RTP, resulting in an oxide thickness of ~110Å. TiN thin films were then deposited directly on SiO2 by a reactive sputtering system. The Ar/N2 flow was changed from 1/6 to 6/6 sccm. RTP was used for the annealing of TiN at 600-800°C for 3 min. Then LPCVD W films were deposited on TiN; the temperature, pressure, and flow rate were 350°C, 0.7 Torr, and WF6/SiH4/H2=5/10/500 sccm, respectively. The LPCVD W/SiO2/Si MOS capacitor was also fabricated to investigate the roles of TiN. As compared to the results obtained from the LPCVD W/SiO2/Si MOS capacitor, the insertion of approximately 20 nm TiN film effectively prohibits the fluorine diffusion during the deposition and annealing of W films, resulting in negligible leakage currents at the low electric fields. In addition, XRD analysis indicated that the preferred orientations of TiN and W films were determined by the change of Ar to N2 ratio. For example, if the ratio of Ar/N2 flow increases, a strong W(211) peak was developed and the resistivity of CVD W-TiN gate slightly decreases. In addition, the flatband voltage of MOS capacitors was shifted to the positive gate voltage when the ratio of Ar/N2 flow increases. We interpreted that this positive shift may be caused by the work-function difference that is caused by the incorporation of N2 during the sputtering process.

### **TF-TuP24** Effect of Interlayer on Thermal Stability of Nickel Silicide, J.S. *Maa*, Y. Ono, F. Zhang, S.T. Hsu, Sharp Laboratories of America, Inc.

Nickel silicide is one of the silicide material for future IC devices with ultrashallow junctions. It has a low Si consumption rate. Low resistance nickel monosilicide can be applied easily to sub-100nm structures. The major challenge is its poor therml stability for film of about 20nm. Here we study the effect of interlayer materials of Ti, Al, Pt, and Pd on the structure and thermal stability of nickel silicide. Ti and Al can enhance the epitaxial growth of nickel disilicide, but Pt can improve the thermal stability of nickel monosilicide. Pd was found not as effective as Pt. By using sequential deposition and RTA annealing, stable silicide can be formed on ultrashallow junction with a 40nm junction depth. It is demonstrated that this structure is stable at 800 degree C with very low junction leakage.

#### TF-TuP25 Optical and Structural Properties of Sol-gel SiO@sub 2@ Layers Containing Cobalt, A. Ramos-Mendoza, H. Tototzintle-Huitle, A. Mendoza-Galván, CINVESTAV-IPN, México; J. González-Hernández, CINVESTAV-IPN, México, Mexico; B.S. Chao, Energy Conversion Devices, Inc.

SiO@sub 2@ layers containing cobalt in the range of 2 to 11 percent in volume were prepared using the sol-gel method. The layers with a thickness of about 600 nm were heat treated in air at 300 and 500 °C. Their structure and optical properties were characterized using optical transmission and reflection measurements, x-ray diffraction and Auger depth profile. The optical transmission data in the UV-visible range, of samples with low cobalt concentrations, show only the absorption bands corresponding to the tetragonal Co, regardless of the heat treatment temperature and the Co concentration. Layers with larger amount of Co, show absorption bands corresponding to both, tetragonal and octahedral Co. When these layers are heat treated, most of the cobalt migrates to the layer surface, being oxidized by the atmospheric oxygen, to form a conducting top layer of Co@sub 3@O@sub 4@, which thickness depends on the heat treatment temperature and Co concentratation. The presence of this top layer has been deduced from optical and Auger depth profile measurements. The cobalt oxide layer thickness ranges from about 100 to 7 nm. In order to describe the absorption bands of both, tetragonal and octahedral Co, it was used the Lorentz oscillator model for the complex effective dielectric function of the SiO@sub 2@ cobalt doped layers. The frequency dependence of the optical constants of the cobalt oxide top layer, in the UV-visible range, was obtained with a generalized Lorentz oscillator model. These latter results are in a good agreement with previous reports.

**TF-TuP26** Perpendicular Magnetic Anisotropy in Ultrathin YIG Films Prepared by Pulsed Laser Deposition Technique, *E. Popova*, *N. Keller*, Versailles University, France; *F. Gendron*, Pierre and Marie Curie University, France; *M. Guyot*, *M.-C. Brianso*, *M. Tessier*, Versailles University, France

The development of high frequency and magneto-optical memory devices increases the interest in thin ferrite film preparation and investigation of their physical properties. A change of these properties is expected when the film thickness becomes of the order of a few lattice parameters. We report on thin and ultrathin yttrium iron garnet (YIG) film preparation by pulsed laser deposition technique. The films deposited on the quartz substrates are polycrystalline with slightly distorted lattice, though the

average lattice parameter is the same as for bulk YIG (12.376 Å). The bulk Curie temperature of 557 K is observed for these films by means of magneto-optical Faraday rotation measurements. However, the saturation magnetization is slightly inferior to the bulk value in the range of 5 - 380 K. Ferromagnetic resonance (FMR) studies of samples with thickness 100 - 3800 Å were performed in different measurement geometries and in the temperature range of 3.5 - 300 K. We observed a change of sign of the effective magnetization (4@pi@M@sub eff@) appearing below a film thickness of approximately 120 Å. The inversion of the easy magnetization direction from in-plane to out-of-plane, i.e. the perpendicular magnetic anisotropy becomes evident above a cross-over temperature which is thickness-dependent. The effective magnetization for a given temperature decreased with decreasing sample thickness. This can be caused by an increasing contribution of the surface anisotropy to 4@pi@M@sub eff@ when the sample thickness is reduced.

TF-TuP27 Mechanical and Structural Characteristics of Nanocrystalline Diamond (NCD) and Diamond-like Carbon (DLC) Coatings, P. Jedrzejowski, Ecole Polytechnique de Montreal, Canada; J. Grabarczyk, P. Niedzielski, S. Mitura, Technical University of Lodz, Poland; J.E. Klemberg-Sapieha, L. Martinu, Ecole Polytechnique de Montreal, Canada

NCD and DLC films are increasingly attractive for the applications such as biocompatible coatings for metallic implants, anticorrosive protection or metallurgical coatings for tools. In the present work we fabricated NCD films by plasma enhanced chemical vapour deposition (PECVD) from methane using a novel high amplitude radiofrequency system. The film microstructure and mechanical properties were evaluated using Raman spectroscopy, elastic recoil detection, AFM, SEM, indentation and microscratch testing. We evaluated the effect of the structured intermediate carbide layer (interphase) on the film performance on substrates for medical applications such as AISI 316L steel, Vitalium and Titanium alloys. Breakdown voltage measured on samples exposed to Tyrod's solution was chosen as an appropriate technique to determine the coatings performance in simulated body environment. The NCD films are compared with standard DLC coatings.

TF-TuP28 Microstructure and Optoelectronic Properties of a-SiGe:H Thin Films Fabricated by the Low Frequency (55 kHz) Glow Discharge, B.G. Budaguan, A.A. Sherchenkov, G.L. Gorbulin, Moscow Institute of Electronic Technology, Russia; A.A. Berdnikov, Moscow Institute of Microelectronics of Russian Academy of Science, Russia; V.D. Chernomordic, Institute of Microelectronics of Russian Academy of Science; A.A. Aivazov, UniSil Corp. The incorporation of Ge in a-Si:H allows to decrease the optical band gap which is necessary for a different optoelectronic applications such as infrared sensors, solar cells, etc. However the increase of Ge content leads to the increase of defects and to the deterioration of the electronic properties. So, the development of the appropriate fabrication technology of a-SiGe:H films is essential. We have shown that a-Si:H films with high electronic properties can be fabricated with using of low frequency (55 kHz) glow discharge. In this work we deposited a-SiGe:H for the first time by this method and investigated the growth mechanism, microstructure and optoelectronic properties of the layers. The a-SiGe:H films were fabricated at different germane content from 0 to 44.5%, and substrate temperatures, T@sub s@, from 175 to 275 °C. It was shown that the high deposition rate of a-SiGe:H is caused by an increased flux of radicals to the growth surface due to the close position of the radical generation region to the electrode. The joint analysis with using of infrared and atomic force microscopy showed that a-SiGe:H films have an island type morphology. The measurements of optoelectronic properties indicate that the decrease of the E@sub g@ with the increase of GeH@sub 4@ is determined by the increase of the concentration of Ge-Si bonds in the interior of islands, while the Si-H@sub n@ and Ge-H@sub n@ bonds are clustered on the island surfaces and does not affect the optical bandgap. The modeling of the photoconductivity showed that density of states distribution does not significantly change with the decrease of T@sub s@. Small decrease of photoconductivity accompanied by large decrease of dark conductivity leads to the high values of photosensitivity at lower temperatures for a-SiGe:H with E@sub g@ as low as 1.5 eV. Thus, 55 kHz glow discharge method allows to fabricate device quality low band gap a-SiGe:H films at low T@sub s@ and high deposition rate.

TF-TuP29 Deposition and Properties of Tetrahedral Carbon Films Prepared on Magnetic Hard Disks, *C.Y. Chan, K.H. Lai, M.K. Fung, I. Bello, R.F. Huang, C.S. Lee, S.T. Lee,* City University of Hong Kong, China; *S.P. Wong,* Chinese University of Hong Kong, China

The areal density of the hard disk doubles every two years. Such substantial increase in disk storage is due to the application of giant magnetoresistance (GMR) heads, new thin film media, and better electronic recording channels. However, such increment cannot be easily attained without reducing the separation between head and magnetic recording medium interface. This can be achieved by using thinner protective overcoating. Here, tetrahedral carbon (ta-C) ultra-thin films were deposited on magnetic hard disk (CoCrTa/Cr/NiP/Al-Mg) by magnetic filtered cathodic arc with variable substrate bias voltage. The resulting films exhibited smoother surfaces than those uncoated disks as indicated by atomic force microscopic measurements and gave rise to a single asymmetric Lorentzian Raman curve shape. Tetrahedral carbon coatings were subjected to an accelerated corrosion test in vapors of concentrated hydrochloric acid for 24 hours. The corrosion test showed the reduced density of corrosion sites when compared to conventional diamond-like carbon (DLC) films. Similarly, the scratch resistance of the ta-C coated disks, investigated by a nanoindenter, showed significant improvement in comparison to DLC films.

#### **TF-TuP30** Properties of Multicomponent Transition Metal Carbide Coatings Prepared by Magnetron Sputtering, S.H. Koutzaki, J.E. Krzanowski, University of New Hampshire

The mechanical and tribological properties of conventional carbide hard coating materials can potentially be improved by developing multicomponent films with nano-scale microstructures. However, the microstructures and phases that form in PVD thin films are often far from equilibrium, so it is necessary to investigate these aspects of candidate multicomponent systems in order to assess their potential as nanostructured hard coatings. Two multicomponent metal carbide systems were investigated in this study, Ti-Mo-C and Ti-W-C. Coatings were fabricated by RF co-sputtering from carbide targets using target combinations of TiC-Mo2C and TiC-WC. Films were deposited on silicon and sapphire substrates at temperatures ranging from room temperature to 650C. The coatings were characterized by XPS, X-ray diffraction, TEM, and nanoindentation. For Ti-Mo-C films, nearly all film compositions were supersaturated solid solutions of Mo in TiC, and multiphase structures could only be obtained in highly Mo-rich films. The hardness of these films generally did not improve with Mo content. Films deposited from TiC and stoichiometric a-WC targets formed only (Ti,W)C solid solutions. The hardness of the sputtered Ti-W-C coatings was in the range of 15-17 GPa, with the exception of one Ti-W-C (40 %W) that had a hardness of 30 GPa. This latter sample was examined using high-resolution TEM, and in comparison to the other Ti-W-C films, was found to have a significantly smaller grain size and a higher film density.

### TF-TuP31 Ferromagnetic Resonance and Magnetic Anisotropy in Epitaxial Fe/Ag Thin Films on GaAs (100), *W. Wu*, University of California, Irvine; *C.S. Tsai*, University of California, Irvine and Academia Sinica, Taiwan; *C.C. Lee*, *H.J. Yoo*, *R. Chuang*, *H. Hopster*, University of California, Irvine

Iron/silver thin films were epitaxially grown on GaAs (100) substrate by molecule beam epitaxy (MBE) system at different growing temperatures and layer structures. Magneto-optic kerr effect (MOKE) experiment was used to measure the magnetization and sample magnetic anisotropy. The common features in the ferromagnetic resonance (FMR) peak-to-peak linewidth @delta@H@sub pp@ are identified, which are dependent on layer structures and growth condition. The measured narrowest linewidth @delta@H@sub pp@ is 26 Oe. We study the coupling between the ultrahigh frequency microwave signal and the spin excitation happened in ferromagnetic Fe thin film. Maximum coupling and thus strong attenuation of the microwave power occur at the FMR frequency f@sub res@ of Fe, as determined by the applied magnetic fields. Microwave notch filter devices were successfully fabricated using the deposited magnetic structures. Because of the high saturation magnetization of Fe film, it is much easy to achieve higher devices operation frequency under relatively lower applied magnetic field. The peak absorption carrier frequency of a propagating microwave has been tuned in a range from 9.6 to 21 GHz in a modest magnetic field from 0 to 2900 Oe for single layer structures. For multilayer structures, peak absorptions are intensified with tuned range from 10.6 to 27 GHz. The experimental results are in good agreement with the theoretical prediction for the case in which the magnetic field is applied along the easy axis of the Fe film. It is desirable to incorporate this kind of magneto static wave (MSW)-based devices in compound semiconductor system, in order to achieve integration into microwave integrated circuits.

TF-TuP32 Importance of Thermal Stress in a Thin Film Lipon Solid Electrolyte, F. Vereda, R.B. Goldner, T. Haas, Tufts University

Because a near term goal of our research is to obtain optimal performance physically vapor-deposited LiCoO@sub 2@/Lipon/C thin film batteries (Lipon = lithium phosphorus oxynitrade), and due to the major importance of the electrolyte in any battery, we have recently been attempting to better understand the causes of electronic shorting that affects our Lipon electrolyte films. After studying the residual and temperature-dependent stress of these films and observing severe cracking after they had undergone a relatively large thermal transient (from 300 °C to room temperature), we adopted a model in which a thermal expansion coefficient mismatch between Lipon and our glass substrates accounts for the cracking and therefore the shorting. This model was also supported by the fact that Al films, which proved to act as a 'buffer layer' and stopped cracking of Lipon when glass/Al/Lipon structures were cooled from 300 °C to room temperature, were successfully used to produce short-free Al/Lipon/Al devices.

TF-TuP33 Structural, Morphological, and Mechanical Properties of Plasma Deposited Hydrogenated Amorphous Carbon Thin Films: Noble Gas Dilution Effects, *L. Valentini*, *J.M. Kenny, G. Carlotti, G. Socino*, Universita di Perugia, Italy; *G. Mariotto, P. Tosi*, Universita di Trento, Italy; *L. Lozzi, S. Santucci*, Universita dell'Aquila, Italy

Recent studies of Ar dilution effects on hydrogenated amorphous carbon (a-C:H) films have been motivated by two factors: the possibility to synthesise diamond films at high temperature@footnote 1@ and the identification of the growth species. One way to pursue this issue consists in the investigation of the effects related to the dilution of methane by rare gases. In this paper a thorough investigation of a-C:H films deposited by rf glow discharge from methane-argon mixtures, for different Ar fractions, onto silicon substrate is presented. The structural, mechanical and morphological properties of these films were investigated by complementary techniques, such as x-ray reflectivity (XRR), Raman spectroscopy, Brillouin light scattering (BLS), tribology and atomic force microscopy (AFM). Experimental results are examined to develop a coherent picture of the relationships between deposition parameters, microstructural features and macroscopic properties, as well as to show how the results are found to be consistent with theoretical calculations@footnote 2@ that relates properties with different chemical composition of the plasmas. The effects due to film deposition parameters such as Ar dilution, applied substrate bias and film properties are discussed in order to clarify which process parameters are important in film formation. @FootnoteText@ @footnote 1@T.G. McCauley, D.M. Gruen, and A.R. Krauss, Appl. Phys. Lett. 73, 1646 (1998). @footnote 2@C. Riccardi, R. Barni, M. Fontanesi, and P. Tosi, to be published.

#### TF-TuP34 Structural Characterization of Tungsten Trioxide Thin Films, L.J. LeGore, R.J. Lad, J.F. Vetelino, B.G. Frederick, University of Maine; E.A. Kenik, Oak Ridge National Laboratory

Tungsten trioxide is a wide band-gap n-type semiconductor which has been used as a sensing material in conductance-type gas sensors. The microstructure and morphology is believed to have a large influence on the sensitivity, selectivity, and stability of the sensor. We have produced tungsten trioxide thin films 15 nm to 600 nm thick by reactive rf magnetron sputtering onto r-cut sapphire substrates. The microstructure of the films was characterized by reflection high energy electron diffraction (RHEED), transmission electron microscopy (TEM), and scanning electron microscopy (SEM). By controlling the substrate deposition temperature and by post-deposition annealing, films from highly oriented epitaxial to random polycrystalline were produced. All films were found to be dense with low porosity. The epitaxial films were nearly atomically smooth while the polycrystalline films were significantly rougher. Lattice parameter measurements at room temperature indicate the possibility of more than one crystallographic phase.

**TF-TuP35 Study on the Oxidation Behavior of Poly Si @sub 1-x@Ge @sub x@ Films, S.-K. Kang**, D.-H. Ko, Yonsei University, Korea; S.-H. Oh, C.-G. Park, Pohang University of Science and Technology, Korea; T.-H. Ahn, M.-S. Joo, Hyundai Electronics Industries Co. Ltd, Korea; K.-C. Lee, D.-Y. Yang, Ju-Sung Engineering Co. Ltd, Korea

We investigated the oxidation behavior of poly Si @sub 1-x@Ge @sub x@ films (X=0.15, 0.42). The samples were oxidized using a conventional furnace in wet oxygen ambient at 700 °C. The composition and thickness of oxide were analyzed by rutherford backscattering spectrometry (RBS) before and after the oxidation using rump simulation. The distribution and chemical bonding of Si, Ge, O elements were analyzed by X-ray photoelectron spectroscopy(XPS). The microstructures of the films were analyzed by HR transmission electron microscopy(TEM). In the case of poly Si @sub 0.85@Ge @sub 0.15@ films, SiO @sub 2@ was formed, rejecting Ge, and subsequently Ge content increased at the SiO @sub 2@/ poly Si @sub 1-x@Ge @sub x@ interface. We observed a small amount of Ge and GeO @sub 2@ in oxide layer by HR-TEM, XPS. In the case of poly Si @sub 0.58@Ge @sub 0.42@ films, we found the formation of both SiO @sub 2@ and GeO @sub 2@ on the poly Si @sub 1-x@Ge @sub x@ films due to the high Ge content. The oxidation rate of poly Si @sub 1-x@Ge @sub x@ increased with Ge content in poly Si @sub 1-x@Ge @sub x@ films under the same oxidation condition.

TF-TuP36 Mechanism of the Isothermic Amorphous-to-Crystalline Phase Transition in Ge:Sb:Te Ternary Alloys, J. González-Hernández, E.F. Prokhorov, Yu.V. Vorobiev, E. Morales-Sánchez, Centro de Investigacion y de Estudios Avanzados del IPN, Mexico; A. Mendoza-Galván, Centro de Investigacion y de Estudios Avanzados del IPN, Mexico, México; S.A. Kostylev, Energy Conversion Devices, Inc.; Y.I. Gorobets, V.N. Zakharchenko, R.V. Zakharchenko, Kiev Politechnic Institute, Ukraine

The kinetics of the isothermic amorphous-to-crystalline (fcc) phase transition at different temperatures has been investigated in alloys with the composition close to Ge@sub 2@Sb@sub 2@Te@sub 5@ which are the most frequently used for erasible optical memory devices. For monitoring the transformation, the electrical resistivity and capacitance measurements were employed as well as the ellipsometry, optical transmission and electron microscopy data. The procedure to determine the transformed volume fraction on the basis of the optical transmission and electrical conductivity data is analyzed. It is shown that the assumption widely accepted about the proportionality between the variation of transmittance or the conductivity and the transformed volume fraction, is seldom correct in the optical case, but never correct in the electrical one; the use of the corresponding procedure could give an error in determination of the crystalline volume fraction of about an order of magnitude. The correct procedure for this case is developed. The transformation kinetics observed agrees with the Johnson-Mehl-Avrami formalism, and gives an average Avrami exponent around 2 and the overall activation energy of about 4.5 eV; the latter value exceeds the previous estimations. The transformation process has the two well-defined stages corresponding to the bulk and surface nucleation of the crystalline phase, the sequence of the stages depends on temperature. It was also found that the ultimate degree of transformation in isothermic experiments is less than 1 and depends upon the transition temperature; the analytical description of this dependence is given. It is shown that this dependence influences the value of the phase transition activation energy determined from the experiment.

## TF-TuP37 Dry Cleaning of Oxide and Contaminaions on Cu Surface in Water Ambient, *H. Ogawa, K. Taniguchi, Y. Horiike,* The University of Tokyo, Japan

A new cleaning method of the Cu bottom surface in via holes and gaps in the ULSI multi-level interconnection was studied employing in-situ XPS (ULVAC-PHI, model 1600). At first, reduction characteristics of the Cu native oxide (CuO and Cu@sub 2@O) on the Cu surface were investigated in N@sub 2@, H@sub 2@, O@sub 2@ and H@sub 2@O ambient at 1 Torr. Analyses of Cu2p@sub 3/2@ photoelectron and Cu@sub LMM@ Auger electron spectra showed that CuO was reduced to Cu@sub 2@O in any ambient above 150 °C of sa mple temperature, because @DELTA@G@sub f@° of Cu@sub 2@O (-146 kJ/mol) is thermodynamically lower than that of CuO (-130 kJ/mol). Cu@sub 2@O was also found to be reduced to Cu in H@sub 2@, N@sub 2@ and H@sub 2@O ambient above 300 °C. H@sub 2@O dose not act as an oxidant for Cu, because @DELTA@G@sub f@° of H@sub 2@O (-229 kJ/mol) is lower than that of the Cu oxide. Next, oxide formation and hydrocarbon (CH@sub x@) and fluorocarbon (CF@sub x@) contaminations of the Cu surface were prepa red by exposure to ICP (inductively coupled plasma) of C@sub 4@F@sub 8@/Ar (unity partial pressure ratio, 20 mTorr of total pressure, 1 kW of 13.56 MHz, V@sub dc@=400V and 2 min) and subsequent O@sub 2@ (100 mTorr, 10 min) plasma. Then the surface was exp osed by the H@sub 2@O vapor ambient at 1 Torr. As a result, almost CH@sub x@ and CF@sub x@ contaminants were removed at 300 °C, and Cu oxides were completely reduced to Cu at 400 °C, while CH@sub x@ contamination was remained in N@sub 2@ and H@sub 2@ ambient at 400 °C. The reason of high removal efficiency of CH@sub x@ and CF@sub x@ in the H@sub 2@O ambient is considered that H@sub 2@O effectively acts as an oxidant and a reducing agent to these contaminations.

TF-TuP38 Characterization of the Reactive Species in an Atmospheric-Pressure Nitrogen Plasma, *G. Ding, S.E. Babayan, G. Nowling, R.F. Hicks,* University of California, Los Angeles

A nitrogen and helium plasma, operating at atmospheric pressure and powered by radio-frequency power at 13.56 MHz, has been investigated to understand the reaction chemistry for plasma-enhanced chemical vapor deposition of nitride materials. Spatial and temporal profiles of excited molecular nitrogen (A, B, and C states) were obtained by optical emission and absorption spectroscopy. In addition, the relative populations of the vibrational states of the ground-state nitrogen molecules were examined. The nitrogen atom concentration was attained by nitric oxide titration and by determining the rate constant for the recombination of nitrogen atoms to form the B state of excited molecular nitrogen. The concentration profiles of all these species were compared with a numerical model of the reacting flow. It has been found that the metastable molecular nitrogen and nitrogen atom concentrations are in the range of 10@super 12@ to 10@super 15@ cm@super -3@. Silicon nitride films were deposited on silicon substrates by combining silane with the effluent from the atmospheric pressure plasma source. Deposition rates of 100 nm/min were observed at substrate temperatures of 400±25 °C. After growth, the optical, electrical, and chemical properties of the films indicated that high quality silicon nitride was produced. The relationship between the film properties and the plasma chemistry will be discussed at the meeting.

### Wednesday Morning, October 4, 2000

### Thin Films Room 203 - Session TF-WeM

Modeling of Thin Film Growth

Moderator: L. Hultman, Linköping University, Sweden

### 8:20am TF-WeM1 Hyperthermal Ion Enhanced Deposition of Materials, J.W. Rabalais, University of Houston INVITED

The chemical and physical interactions of ions with surfaces in the energy range 5 eV to several keV will be described. Hyperthermal reactive ions impinging on surfaces provide a method for deposition/growth/synthesis of materials within a unique nonequilibrium UHV environment, giving rise to the technique of ion beam deposition (IBD). IBD allows independent control over parameters such as ion energy and type, ion fluence and dose, substrate temperature, and background gases. The depth of penetration/interaction of the impinging ions with the surface is determined by the ion kinetic energy. The excellent control over ion dose allows deposition of thin films, e.g. < 30 @Ao@, with sharp film-substrate interfaces. The UHV conditions in the sample chamber allow deposition onto atomically clean and well-ordered surfaces. In situ diagnostic techniques, such as reflection high energy electron diffraction (RHEED), xray photoelectron spectroscopy (XPS), Auger electron spectroscopy (AES), mass spectrometry, and a microbalance allow direction characterization of the deposited/reacted layers. Examples of the use of mass- and energyselected beams for hyperthermal surface reactions, film growth, and shallow implantation will include: Si+ ion homoepitaxy, growth SiO2 and TiSi2 films on silicon, growth of Ti and TixAlyOz films on sapphire (a-Al2O3), controlling cationic diffusion coefficients in sapphire, and interactions of chlorotitanium ions TiClx+ with graphite and silicon surfaces.

### 9:00am **TF-WeM3 Thin-Film Growth on Polymer Surfaces through Polyatomic Ion Deposition: Molecular Dynamics Simulations**, *Y. Ji, S.B. Sinnott,* The University of Kentucky

Ion deposition on polymer surfaces is widely used to deposit polymer thin films or modify the mechanical properties of the polymer surface. In this work the reactions of polyatomic ions with a polystyrene surface are investigated through classical molecular dynamics simulations. The classical reactive empirical bond order potential is used.@footnote 1@ The particular ions of interest are CH@sub 3@@sup +@ and C@sub 3@H@sub 5@@sup +@ which are deposited over a range of energies from 20 to 100 eV. The chemical reactions that occur on impact are shown to depend heavily not only on the incident energy but also on the structure and size of the ion. Information about penetration depths and energy transfers are also obtained from the simulations. The results are compared to experimental data obtained for the growth of fluorocarbon thin films through the deposition of the comparable fluorocarbon species on polystyrene. There is generally good agreement between the experimental and computational results.@footnote 2@ The simulations also address the effect of incident angle on the results of ion deposition. The differences between the reactions that occur at normal incidence and at various angles are discussed. This work is supported by the National Science Foundation (CHE-9708049). @FootnoteText@ @footnote 1@.S.B. Sinnott, L. Qi, O.A. Shenderova, D.W. Brenner, in Chapter 1 of Volume IV of ADVANCES IN CLASSICAL TRAJECTORY METHODS, Molecular Dynamics of Clusters, Surfaces, Liquids, and Interfaces, Ed. W. Hase (JAI Press, Inc., Stamford, CT, 1999), pp. 1-26. @footnote 2@M.B.J. Wijesundara, L. Hanley, B. Ni and S.B. Sinnott, Proceedings of the National Academy of Science, USA 97 23-27 (2000).

9:20am TF-WeM4 Molecular Dynamics Simulation of Ion Bombardment on Hydrogen-terminated Si(001)-(2X1) Surfaces, *K. Satake*, Mitsubishi Heavy Industries, Ltd., Japan; *D.B. Graves*, University of California, Berkeley In crystalline Si growth using low-temperature plasma enhanced chemical vapor deposition (PECVD), it is important to clarify the role of ions in the surface reactions. We present here the interaction between an Hterminated Si(001)-(2X1) surface and normal incident SiH@sub 3@@super +@ and H@sub 2@@super +@ ions as a function of the incident energy (10 eV, 20 eV, and 40 eV) using molecular dynamics (MD) simulations. SiH@sub 3@@super +@ was observed to penetrate less than 3-4 Å at 10 eV and 20 eV, increasing to about 5 Å at 40 eV. H@sub 2@@super +@ penetrated the surface only slightly at 10 eV, but the penetration depth increased rapidly with increasing energy. At 40 eV, H@sub 2@@super +@ was observed to penetrate up to 20 Å, or even farther. Per trajectory, SiH@sub 3@@super +@ was observed to displace about 4 Si atoms in the lattice, an average distance of about 2-3 Å, at 40 eV. H@sub 2@ @super +@, by contrast, displaced on average, only 0.7 Si atoms per trajectory, and the displacement distance was about 1.5 Å, at 40 eV. It is suspected that ion impact creates sites which react more readily with neutral species. The generation rate of dangling bonds (DB) at the surface due to H@sub 2@ @super +@ ion impact is about twice that of SiH@sub 3@ @super +@ ions for the energies studied. In the DB generation by H@sub 2@ @super +@ ions, the primary process is direct surface H atom sputtering. In addition, we also observed the DB generation with dihydride and monohydride formation by H insertion into the Si dimer and H exchange. In the case of SiH@sub 3@ @super +@ ions, the probability of DB generation by direct sputtering is almost the same as that of insertion; however, in addition, the near-surface crystallinity is disrupted in most of the trajectories. The H@sub 2@ @super +@ ion bombardment under 20 eV, by contrast, can enhance the surface reactivity by creating defects only in the top surface layer without damaging the crstallinity of the underlying silicon.

9:40am **TF-WeM5 Low Temperature Growth of 2D Pb Islands on Si(111)7x7 Surfaces, C.S. Chang**, Academia Sinica, Taiwan, ROC; S.H. Chang, National Tsing Hua University, Taiwan, ROC; *W.B. Su, C.M. Wei,* Academia Sinica, Taiwan, ROC; *L.J. Chen*, National Tsing Hua University, Taiwan, ROC; *TienT. Tsong*, Academia Sinica, Taiwan, ROC

Lead (Pb) is known to grow on Si(111) with the Stranski-Krastanov (SK) mode at room temperature. With the variable temperature scanning tunneling microscopy, we study the low temperature growth of Pb films on the Si(111)-7x7 surface from T ~40 K to 200 K. The islands are formed after the completion of the wetting layer and display peculiar properties that cannot be categorized into any of the conventional growth modes. Their tops are all very flat and even more surprisingly, they prefer to grow into some discrete thicknesses corresponding to 4, 7 and 9 atomic layers. Among them, that equivalent to seven atomic layers is especially dominant. While the stress in heteroepitaxy may be the only dominant factor for a thick film and hence causes the film to form into 3D islands, for a thin film some other effects may be in play to counterbalance the stress. One of such effects is the "quantum size confinement", which could reduce the system energy due to quantization of the confined electrons in the film. Preliminary ab initio calculations seem to support this theory.

#### 10:00am **TF-WeM6 Modeling of Cluster Ion-Surface Interactions with Full Inclusion of Internal Degrees of Freedom**, *K.J. Boyd*, University of New Orleans; A. Lapicki, S.L. Anderson, University of Utah

Molecular dynamics simulations with embedded atom or tight binding moment approximation potentials are used to investigate the interactions of small cluster ions (N<50) with metal surfaces. The simulations are performed at constant target temperature, with the cluster initially thermostatted independently. This allows the internal vibrational and rotational degrees of freedom of the cluster to be treated properly. At room temperature, the vibrational energy content of a 50 atom cluster may be several eV, which is comporable to the translational energy of the cluster. The rotational energy at room temperature is much lower, but the effect of cluster rotations is to change the momentum of cluster atoms such that they impinge at non-normal incidence on the target. This nonnormal momentum component may alter the dynamics of cluster deposition by changing the fragmentation and penetration behavior.

## 10:20am TF-WeM7 Extension Velocities for Level Set Based Surface Profile Evolution, *D.F. Richards*, *S. Sen, M.O. Bloomfield, T.S. Cale,* Rensselaer Polytechnic Institute

Level set based front-tracking methods represent an attractive alternative to more traditional node and segment based approaches to tracking interface motion. Level set methods avoid many topological difficulties which arise in node-moving schemes and are easily extended to three dimensions. However, level set methods also require knowledge of the speed function at every point in the solution domain. This is a somewhat troublesome requirement for profile evolution models since the interface speed may have no physical meaning at points that are not on the surface. The solution to this problem is to formulate extension velocities that in some way extrapolate speeds from the interface to other points in the solution domain. We compare several different methods for determining extension velocities and discuss the characteristics of node and segment approach that are helpful in calculating extension velocities.

### Wednesday Morning, October 4, 2000

10:40am TF-WeM8 Models of Electrochemical Deposition of Copper Thin Films:The Effect of Leveling Agents, S. Soukane, T.S. Cale, Rensselaer Polytechnic Institute

As device sizes decrease, the ability of electroplating to create conformal films in deep features make it very attractive. Especially beneficial in interconnect applications is the "leveling" effect of certain organic additives. With the use of these leveling agents, electroplating offers the possibility of a superfilling effect, leading to void-free structures. This effect is often attributed to the inhibition of plating along feature sidewalls. Much feature-scale modeling work has been focused on reproducing the effect of the additive during deposition. The inhibition has been assumed to be due to operation at a mass transport-limited rate that allows the leveling agent to be completely depleted in the region near the surface. This may be a good assumption if the agent is highly reactive and used in quantities on the order of hundreds of ppm. Its inhibiting effect is usually correlated to the expression of the current density by a factor that is a function of the leveling agent flux to the surface. This approach limits the opportunities to look for explanations via chemical mechanisms. We show that the leveling effect can be explained via a more detailed chemical mechanism involving adsorbed species. We present a feature-scale model coupling the potential and concentration fields via the current density at the feature surface, together with a chemical mechanism involving surface species. In this chemical mechanism, copper ions go through two successive irreversible reactions. The first step is a charge transfer reaction, leading to an adsorbed copper species on the surface. The second is much faster, consisting of the adsorbate reduction and insertion into the film. It is assumed that the leveling agent is completely transformed on the surface to new species that play the important roles in the inhibition effect. These proposed surface species can undergo slow desorption reactions or can be incorporated in the solid at a rate much slower than copper insertion.

### Wednesday Afternoon, October 4, 2000

### **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 Hydrogenated 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.

### Wednesday Afternoon, October 4, 2000

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.

### Plasma Science and Technology Room 310 - Session PS1+TF+SE-ThM

### Fundamentals of Plasma Enhanced Chemical Vapor Deposition

Moderator: A. von Keudell, Max-Planck-Institut für Plasmaphysik

8:20am PS1+TF+SE-ThM1 Analysis of Pulsed O@sub 2@/TEOS Helicon Plasmas by Time-resolved Optical Spectroscopy, *A. Granier*, Institut des Materiaux de Nantes, France; *A. Rousseau*, Laboratoire de Physique des Gaz et des Plasmas, France; *L. Le Brizoual*, Institut des Materiaux de Nantes, France

The use of pulsed plasmas instead of continuous plasmas in Plasma Enhanced Chemical Vapor Deposition is known to improve film quality and adherence, due to the reduction of stress. Here, pulsed low pressure (2 mTorr) helicon oxygen/tetraethoxysilane (TEOS) plasmas are investigated by time-resolved optical emission spectroscopy in order to monitor the kinetics and lifetime of radical species in the plasma-off and plasma-on periods. The 300W rf power is 100% modulated and the duty cycle is varied from 1 to 500 Hz. The time behavior of Ar (750 nm), O (844 nm), H (486 nm), OH (306 nm) and CO (296 nm) emissions in the diffusion chamber are studied. The Ar line takes less than 100 microseconds to reach its equilibrium. The H. OH. O and CO intensities take significantly greater times to equilibrate due to the relatively long lifetime of their ground states, and it was necessary to go to a duty cycle of 1 Hz, including a 130 ms plasma-on time and a 860 ms plasma-off time to reach the stationary state. Under the plasma conditions investigated (a 2 mTorr pressure including a TEOS partial pressure of 0.2 mTorr) the OH, O, H intensities take about 1ms, 40ms and 80 ms, respectively to reach their equilibrium. In addition, their intensities normalized to the Argon line intensity increase from a value close to zero at the ignition time, which indicates that the excited states of OH, O, H radicals are created by electron impact excitation on their ground-states and that these radicals have completely disappeared after 860 ms. In contrast, the normalized CO intensity increases from almost zero but has not yet reached its equilibrium after 130 ms, which is consistent with the fact that CO is a stable molecule which is lost by convection to the pump. Additional results obtained in pure oxygen plasmas are also presented and compared to those obtained in O@sub 2@/TEOS plasma.

#### 8:40am PS1+TF+SE-ThM2 Aluminum Oxide Deposition in an Ionized PVD System, N. L<sup>1</sup>, D.N. Ruzic, University of Illinios, Urbana-Champaign; A. Paranjpe, CVC Inc.; J.E. Norman, J.P. Allain, University of Illinios, Urbana-Champaign

An Aluminum target of a planar magnetron system is powered by a pulsed DC plasma generator to deposit AlOx film using a mixture of Ar and O2. Compared with the conventional sputtering magnetron system, the pulsed directed current (DC) bias is able to discharge the accumulated ions on the insulating AlOx film surface effectively during the positive duty cycle. The chamber also contains a secondary radio-frequency (RF) plasma source to ionize the sputtered metal neutral flux, and generate oxygen atoms and radicals. The directionality of the ion flux can be important for high aspect ratio features. The deposition rates of AI and AIOx films as a function of O2 partial pressure vs. Ar are examined with and without the RF plasma. The deposition rate of AlOx with 400 Watts RF is actually much higher than the deposition rate of Al without the RF at the same total pressure of 25mTorr. Hysterisis curves showing the transition point from metallic mode to poison mode at a certain partial pressure are presented. The presence of a secondary plasma producing ionization makes the metallic sputtering mode possible at a higher O2 partial pressure. A gridded energy analyzer and a guartz crystal microbalance (QCM) are embedded in the substrate plane to allow the ion and neutral deposition rates to be determined. Electron density and electron temperature changes caused by the RF power are measured by a Langmuir Probe. SEM photos of deposited films show differences in film quality as a function of RF power.

### 9:00am PS1+TF+SE-ThM3 Surface Transport Kinetics in Plasma Deposition of Hydrogenated Amorphous Silicon, K.R. Bray, A. Gupta, G.N. Parsons, North Carolina State University

The concept of dynamic scaling was developed to help understand the role of kinetic phenomena that occur on surfaces during non-equilibrium processes (such as film deposition). Plasma deposition of a-Si:H is particularly intriguing because it is well known that over a wide

temperature range, kinetic growth process results in very smooth (nonrandom) surface texture indicating significant surface species transport, but the growth rate is not thermally activated. We have used rf plasma deposition to form a-Si:H films with both helium and argon diluted silane, and used dimensional and frequency analyses to analyze surface topography obtained from AFM images. Surface fractal scaling parameters, including static (a) and dynamic (b) scaling coefficients, Fourier index, saturation roughness, and lateral correlation length (Lc), were determined as a function of film thickness and temperature. After film coalescence (15-20 s) the scaling coefficients are consistent with the surface topology being described as a self-similar structure; a is constant with growth time and is ~1.0, b is ~4.0, and the saturation roughness value increases exponentially with time as tb/a. Based on Herring's models of surface transport, the scaling coefficient values are consistent with surface smoothening being driven by diffusion. In this picture, the lateral correlation length can be equated with the surface diffusion length. We find that Lc ranges from ~50 to 200nm, and is thermally activated, corresponding to a diffusion activation energy of ~0.2eV. This result has important implications for current growth models, where diffusion length is proposed to decrease with increasing temperature because of increasing density of diffusionterminating dangling bond sites. Possible modifications to current models, consistent with our observed data, will be discussed and presented.

9:20am **PS1+TF+SE-ThM4 Hydrogenated Amorphous Silicon Fractal Growth and its Relation to the Growth Mechanism**, *A.H.M. Smets*, Eindhoven University of Technology, The Netherlands; *D.C. Schram*, Eindhoven University of Technology, The Netherlands, Netherlands; *M.C.M. van de Sanden*, Eindhoven University of Technology, The Netherlands

The roughness evolution of the anorphous hydrogenated amorphous silicon (a-Si:H) growth has been studied using in situ HeNe ellipsometry. The a-Si:H depositions are performed using expanding thermal plasma (ETP) deposition technique. With the ETP technique it is possible to grow a-Si:H under dominantly SiH@sub 3@ flux conditions with growth rates ranging over two orders magnitude (1-100 Å/s). The roughness evolution can be divided in an initial growth phase corresponding to a nucleation phase followed by a post initial phase in which the a-Si: H bulk is grown. The post initial growth phase can be described following the universal scaling law, i.e. the roughness scales as t@super beta@ where t is the time and @beta@ the dynamic scaling exponent which depends on the surface relaxation mechanism. The measured scaling exponent @beta@ for growth rates equal or smaller than 22 Å/s is temperature dependent and drops from 0.5 at 100 Celsius down to 0.06 at 500 Celsius. A simple solid on solid (SOS) model is introduced, based upon an activated site at which growth can occur and which can diffuse with a site dependent surface diffusion. With this model the temperature dependent @beta@ can be simulated and the activation energy of the diffusion mechanism can be deduced without the knowledge which process is really responsible for the surface relaxation. The obtained activation energy is equal to ~ 1.0 eV on a terrace site, much higher then what would be expected from physisorbed SiH@sub 3@ dominated a-Si:H growth. At higher growth rates (70 Å/s) the @beta@ shows a maximum around 300 C Celsius. The obtained @beta@ at low temperatures and high deposition rates corresponds to a phase in which the roughness evolution tends more to ballistic fractal growth. Possible relaxation mechanism to explain the high diffusion activation energy will be discussed.

9:40am PS1+TF+SE-ThM5 Interactions of Chemically Reactive Radicals with Si Growth Surfaces during Plasma Deposition of Si Thin Films, S. Sriraman, University of California, Santa Barbara, U.S.A; S. Ramalingam, E.S. Aydil, D. Maroudas, University of California, Santa Barbara

Hydrogenated amorphous silicon (a-Si:H) thin films grown by plasma deposition from SiH@sub 4@ containing discharges are widely used in photovoltaic and flat-panel display technologies. The structural quality and electronic properties of the deposited films depend on the identities and fluxes of chemically reactive species that originate in the plasma and impinge on the growth surface. Atomic-scale simulations of radical-surface interactions are of utmost importance in understanding the fundamental mechanisms of the deposition process. In this presentation, moleculardynamics (MD) simulations of radical-surface interactions during deposition of a-Si:H from chemically reactive radicals, SiH and SiH@sub 2@, are analyzed. The simulations reveal a broad class of reaction mechanisms and predict surface reaction probabilities that are in good agreement with experimental measurements. The growth of a-Si:H films starting from an initial H-terminated dimerized Si(001) surface is studied through MD simulations of repeated impingement of the individual radical precursors. Special emphasis is placed on the identification of the

elementary surface chemical reactions that govern the deposition process. Effects of the reactions on the growth surface are examined by analyzing local structural configurations and surface chemical reactivity in the vicinity of the surface reaction sites. Evolution of the films' structure, surface morphology and roughness, surface reactivity, and surface composition are analyzed in detail and comparisons made with similar films deposited from individual SiH@sub 3@ precursor. The resulting surface hydride compositions in the deposited films are compared with experimental data. The comparisons are used to discuss our current understanding of the deposition process and implications for plasma deposition of a-Si:H.

### 10:00am PS1+TF+SE-ThM6 SiH@sub x@ Radical Densities in a Remote SiH@sub 4@ Plasma for High Rate Deposition of a-Si:H, W.M.M. Kessels,

J.P.M. Hoefnagels, M.G.H. Boogaarts, Eindhoven University of Technology, The Netherlands; D.C. Schram, Eindhoven University of Technology, The Netherlands, Netherlands; M.C.M. van de Sanden, Eindhoven University of Technology, The Netherlands

The ground state densities of SiH@sub x@ radicals in a remote Ar-H@sub 2@-SiH@sub 4@ plasma used for high rate deposition of device quality a-Si:H (up to 100 Å/s) have been investigated in detail by cavity ring down absorption spectroscopy (CDRS) and threshold ionization mass spectrometry (TIMS). SiH@sub 3@ has been measured by CRDS using the broadband à @super 2@A@sub 1@ <- @td X@ @super 2@A@sub 1@ absorption peak at 200 - 260 nm and revealed very good agreement with the TIMS measurements on SiH@sub 3@. SiH@sub 2@ has been measured by TIMS and SiH and Si by CRDS on the transitions A @super 2@@DELTA@ <- X @super 2@@PI@ (~414 nm) and 3p4s <- 3p@super 2@ (~251 nm), respectively. The generation and loss processes for the silane radicals have been investigated thoroughly for different plasma conditions and the contribution of the radicals to film growth has been determined. It is shown that for optimum a-Si:H film properties, the contribution of SiH@sub 3@ is approximately 90%, of SiH@sub 2@ is smaller than 5%, of SiH is ~2%, and of Si is 0.2%. For these conditions, the spatially resolved axial and radial SiH@sub 3@ densities in the plasma are compared with 2-D axisymmetric fluid dynamics model calculations using Phoenics CVD, in which the basic gas phase and surface reactions are taken into account. Furthermore, the first time-resolved silane radical measurements in a modulated rf biased plasma for the determination of the radicals' surface reaction probability will be presented.

## 10:20am PS1+TF+SE-ThM7 Fundamentals of Plasma Enhanced Chemical Vapor Deposition, J. Meichsner, Ernst-Moritz-Arndt-University Greifswald, Germany INVITED

Applications of non-isothermal plasmas for chemical vapor deposition and plasma surface modification imply the understanding of the fundamental problem: the plasma-surface interaction. From the plasma physics point of view the transition between the gas plasma and the solid state is characterized by the plasma sheath in front of the surface which controls the flux and kinetic energy of the charged particles. Additionally, in a reactive molecular plasma the complex chemical reactions must be taken into account in the gas phase and at surfaces. Depending on nature of molecular gases, surface material and plasma properties the modification of a thin surface layer, etching or thin film deposition may be found simultaneously on electrodes, immersed samples or surrounding walls. Insitu diagnostic tools are preferably qualified to provide detailed information about processes in the gas plasma and at surfaces. The experimental investigations involved plasma diagnostics by means of optical spectroscopy (OES, LIF) and mass spectrometry (energy selective ion analysis, electron attachment mass spectrometry) as well as surface and thin film characterization using special methods of FTIR-spectroscopy (IRRAS, ATR, fiber based), ellipsometry and microgravimetry. In a low pressure rf-discharge of Hexamethyldisiloxane the chemical conversion of the monomer gas into new stable gas molecules and deposition of a thin organic film were investigated in dependence on characteristic process parameters. The changed atomic composition and molecular structure of the organic films were connected with varied film properties interesting for semipermeable membranes, photo-conducting films, optical or protective coatings. In fluorocarbon plasmas the investigation of the Polyethylene and Polystyrene surface modification as well as thin film deposition revealed the dynamics between incorporation of atoms/molecules and etching of surface material.

11:00am PS1+TF+SE-ThM9 Thin Film Growth via Surface Reactions of CH@sub 3@, C@sub 2@H@sub 2@ and H as Investigated by Radical Beam Experiments, *M. Meier*<sup>1</sup>, *A. von Keudell*, Max-Planck-Institut für Plasmaphysik, Germany

The knowledge about surface reactions of hydrocarbon radicals is a key element for the understanding of thin film growth in low temperature plasmas using hydrocarbons as precursor gas. Besides the formation of hard coatings by using an additional ion bombardment during growth, it is possible to deposit polycrystalline diamond at elevated substrate temperature from a methane discharge diluted in 99 % hydrogen. The dominant species which are believed to be responsible for diamond formation are atomic hydrogen together with either CH@sub 3@ or C@sub 2@H@sub 2@. In our experiment, we employ particle sources for the production of quantified beams of the radicals CH@sub 3@ and H and for C@sub 2@H@sub 2@ molecules to study the interaction of these species with a hydrocarbon film surface. The emitted fluxes of these beam sources are quantified by using angular resolved ionization threshold mass spectrometry. Recently it has been shown that the sticking coefficient of CH@sub 3@ increases from 10@super -4@ to 10@super -2@ if atomic hydrogen reacts simultaneously with the growing film surface at a low substrate temperature of 320 K. A similar experiment using C@sub 2@H@sub 2@ and H revealed no significant growth via C@sub 2@H@sub 2@ adsorption at the film surface. The variation in the film composition during the synergistic growth is monitored via in situ real time infrared spectroscopy. From the interpretation of these spectra a growth synergism for the simultaneous interaction of CH@sub 3@ and C@sub 2@H radicals with the film surface is observed. This demonstrates that the various synergisms between the growth precursors have to be taken into account for a consistent description of thin film growth via radical adsorption.

## 11:20am PS1+TF+SE-ThM10 Deposition Kinetics in Methane rf Glow Discharges: A Combined Experimental and Modeling Study, J.R. Doyle, D. Cole, B. Magocsi, Macalester College

Methane rf glow discharges are commonly used for diamond-like carbon deposition, but in spite of many experimental and theoretical studies, the details of the plasma chemistry, and in particular the identity of the dominant film precursors, are still debated. In this work we present a comprehensive model of the film deposition using a "semi-empirical" approach. Optical emission measurements and measured electrical properties of the discharge are combined with a Particle-in-Cell/Monte Carlo (PICMC) simulation, which is then used to calculate ion and neutral radical production rates and profiles. Diffusion-reaction-drift (fluid) equations are then solved for stable gas production and ion and radical transport to the electrode surfaces. The model is corroborated by mass spectrometry measurements of the stable gas partial pressures. Film growth rates are calculated from the model and are compared to measured growth rates as a function of pressure and power on both the grounded and powered electrode. The results suggest that C@sub n@H@sub m@ radicals and ions with n > 1 are the dominant sources of mass deposition under conditions used to produce diamond-like films.

## 11:40am PS1+TF+SE-ThM11 Using Plasma Energetics to Influence Silicon Nitride Step Coverage, K.L. Seaward, Agilent Technologies; M.L. Jezl, University of Wisconsin, Madison

PECVD silicon nitride is widely used in the fabrication of electronic and optical devices, integrated circuits, and display devices. An important characteristic of PECVD silicon nitride is step coverage, which describes how well the deposition conforms to features that are being coated. Both high and low step coverage are technologically important. In the present work, we investigate altering the plasma energetics to change the amount of PECVD silicon nitride deposited on the underside of structures. Models that predict such step coverage suggest that the precursor sticking coefficient is the dominant factor. Accordingly, different inert gases were added to the deposition plasma to either increase or decrease sticking coefficients by way of increasing or decreasing the plasma electron energy. Depositions were run with 4% ammonia, 1% silane, and 95% He, Ar, Xe, or N@sub 2@. Deposited films were characterized by etch rate, stress, FTIR, Auger, and SEM. Deposition plasmas were characterized by optical emission and rf tuning parameters. The only characteristic related to step coverage was the ratio of N-H bonds to Si-H bonds in the films. Since PECVD silicon nitride films have between 10% and 30% hydrogen content, it is expected that hydrogen plays a large role in film properties. What appears to happen for step coverage is a change in bonding configuration from nitrogen being primarily three-fold coordinated to silicon (high step

<sup>1</sup> PSTD Coburn-Winters Student Award Finalist

coverage) to nitrogen being primarily two-fold coordinated to silicon with the third bond being to hydrogen (low step coverage). This latter material, called silicon diimide, is a chemical analog of SiO@sub2@ which, when plasma-deposited with silane, also has low step coverage. This analogy with SiO@sub2@ deposition suggests that precursor sticking coefficients are high during formation of silicon diimide, and this occurred most prominently with mixtures of He and N@sub2@ present in the plasma.

### **Thin Films**

Room 203 - Session TF-ThM

#### **Optical Films**

Moderator: W.T. (Pat) Beauchamp, OCLI/JDSU

8:20am **TF-ThM1 Optical Thin Film Multilayer Systems for Thermal Emittance Modulation in the 300K Blackbody Spectral Region**, *C.L. Trimble, E.B. Franke*, University of Nebraska, Lincoln; *J.S. Hale,* J.A. Woollam Company, Lincoln; *M. Schubert*, *J.A. Woollam*, University of Nebraska, Lincoln

We report on all-solid state electrochromic multilayer systems for thermal emittance modulation in the 300 K blackbody spectral region (2 to 40 microns). Amorphous and polycrystalline WO@sub 3@ thin films were used as ion storage and electrochromic layers, respectively. Tantalum oxide thin films were used as ion-conductor layers. All films were grown by magnetron sputtering. The multilayer system was switched between low and high emittance states by application of small voltages between two enclosing the stack, thereby moving previously electrodes electrochemically inserted Li@super +@ from the electrochromic to the storage layer and back. Two electrode designs were tested. One was built with an aluminum bottom layer electrode and an aluminum grid top electrode, and a second was made with aluminum grid electrodes on top and bottom. The optical constants of Li@super +@ intercalated and deintercalated tantalum oxide and WO@sub 3@ thin films were measured by ellipsometry from 2 to 35 microns. Prior to experimental layer stack formation, the thin film layer structure was optimized by calculations of emittance modulation based on the single layer optical constants and thicknesses. Performance of the layer stack was obtained by reflectance modulation @DELTA@R from 2 to 40 microns, and related to spectral emittance. Reflectance spectra were further used to calculate the emissivity modulation @DELTA@@epsilon@ integrated over a 300 K blackbody spectrum. Calculations also suggest application of thermal emittance modulating multilayers for temperatures up to 900 K. Additional simulations were performed assuming the layer stack covered by either a ZnS or a MgF@sub 2@ layer. Cover layers should protect the WO@sub 3@ layer, prevent Li@super +@ chemical reactions and moisture incorporation, and act as optical impedance match to improve switching performance. Supported by BMDO # DSAG60-98-C-0054, NASA Glenn Research Center grant # NAG3-2219, and NASA Epscor grant # NCC5-169.

8:40am TF-ThM2 Structural Characterization of High and Low Index PECVD Optical Coating Materials: The Case of Titanium Dioxide and Silicon Dioxide, *V. Hajek, M. Latreche, J.E. Klemberg-Sapieha, L. Martinu,* Ecole Polytechnique, Canada; *A. Argoitia, W.T. Beauchamp,* Optical Coating Laboratory Inc.

In the present work we systematically study the optical, mechanical and structural characteristics of high index TiO@sub2@ and low index SiO@sub2@ films prepared by plasma enhanced chemical vapor deposition (PECVD) under controlled ion bombardment conditions. The films were obtained either individually from titanium tetrachloride (TiCl@sub4@), hexamethyldisiloxane (HMDSO), silicon tetrachloride (SiCl@sub4@) or from TiCl@sub4@/SiCl@sub4@ or TiCl@sub4@/HMDSO mixtures. Depositions were performed using radiofrequency (13.56 MHz) or dualmode microwave/radiofrequency low pressure plasma systems; the latter one allows for a selective control of the ion energy and ion flux. In the first series of experiments we show that depending on the substrate bias voltage and temperature the refractive index for TiO@sub2@ at 550 nm varies from 2.20 to 2.40, the extinction coefficient remains low (k  $\sim$  1-5 x 10@super-5@), and the film microhardness of about 10 GPa and low stress (0 - 200 MPa in compression) point to good film mechanical integrity. In the second series of experiments we study the transition from amorphous to crystalline structure, chemical bonding, and the role of chlorine in TiO@sub2@, SiO@sub2@ and mixed TiO@sub2@/SiO@sub2@ systems using ERD, XRD, FTIR, microraman, SEM and TEM techniques. The evolution of the microstructure is related to the energetic conditions during the film growth.

9:00am **TF-ThM3 Porous Thin Film Microstructure Control for Tuned Optical Properties**, *J.C. Sit*, *S.R. Kennedy*, *M.J. Brett*, University of Alberta, Canada

The technique of glancing angle deposition (GLAD) has been used to produce highly porous thin film media by exploiting the enhanced atomic self-shadowing encountered with highly oblique angle deposition. Using advanced substrate motion with this technique allows for a great deal of control over the columnar morphology in these porous films. GLAD films with "helical" or chiral morphology have been shown to possess unique optical response including optical rotation and circular dichroism. As the structural parameters of the film determine many of the optical properties, careful control over the structural parameters is critical. For example, the wavelength at which peak optical activity is observed may be engineered to fall within the UV, visible, or NIR regions by appropriate control of the helical pitch. We present here characterization of the optical response with respect to several structural parameters in optical GLAD films including helical pitch and radius. Further, we apply similar characterization to several other microstructural types of interest such as periodically bent nematic (planar "s"-shaped) morphologies.

### 9:20am TF-ThM4 Development of a PECVD Antireflective Layer for 193nm Polysilicon Gate Applications, *W. Fan*, *Y. Wang, K. MacWilliams, J. Tian, Z. Karim*, Novellus Systems, Inc., U.S.; *K. Ring*, Conexant Systems, U.S.

A PECVD silicon oxynitride film used as an antireflective layer (ARL) has been developed for patterning sub-0.15µm polysilicon gate at 193nm wavelength. PROLITH/2@super TM@ simulations were carried out to determine the range of optical parameters which results in minimum substrate reflectivity (e.g., a few tenths of one percent). An oxynitride film with n ~ 1.80, k ~ 0.60, and t ~ 260Å, which offers less than 0.1% reflectivity, can be successfully deposited by a typical sequential PECVD chamber. In conjunction with achieving a film with these parameters, film deposition process window, film measurement variation, and posttreatment effects were taken into consideration to ensure minimal reflectivity. Finally, the films were patterned with 193nm photoresists. Cross-section SEM shows tight CD control.

### 9:40am TF-ThM5 Characterizing Bi-Layer ARC for Advanced Lithography, *I. Bloomer*, *D.V. Likhachev*, *J. Lam*, *D. Harrison*, n&k Technology

Bi-layer ARCs consisting of Si@sub3@N@sub4@/Si-rich SiN@subx@/Sisubstrate are gaining attention for advanced lithography applications. Such bi-layer ARCs are more effective than single-layer ARCs in reducing standing waves, and furthermore provide wider processing latitude for overall ARC thickness. The processing conditions for a stoichiometric film such as Si@sub3@N@sub4@ are well controlled, and therefore its index of refraction, n, and the extinction coefficient, k, are well established. By contrast, the n and k values of a silicon-rich SiN@subx@ film are variable and strongly dependent on the gas distribution of the processing chamber. Typically the output is a film with non-uniform composition along the zaxis. For such bi-layer ARCs, rapid and accurate characterization is imperative to produce a consistent, uniform product. We will present a metrology technique, based on the 'n&k Method', that accurately and rapidly characterizes bi-layer ARCs despite variations and non-uniformities. With this method, the thicknesses of both the Si@sub3@N@sub4@ and the non-uniform silicon-rich SiN@subx@ layers are determined simultaneously, along with the n and k spectra (190 to 1000nm) of the nonuniform silicon-rich SiN@subx@ layer, which is determined as a function of z. The "n&k Method― is based on broad-band reflectance that incorporates all-reflective optics to provide a signal-to-noise ratio of better than 0.2% over the entire measured wavelength range of 190 to 1000nm. The Forouhi-Bloomer model for n and k is used to analyze the raw data. Results for a series of samples with silicon-rich SiN@subx@ thicknesses ranging from 180 to 300 Å and the Si@sub3@N@sub4@ thicknesses ranging from 1000 to 1300 Å will be presented, along with the results of the z-direction compositional non-uniformity of the silicon-rich SiN@subx@ layer. We will also discuss how these results can be used to optimize the manufacturing process for bi-layer ARCs.

10:00am TF-ThM6 A Near-grazing-incidence, Antireflective Coating for 121.6 nm for a Mars-bound Neutral Particle Detector., S. Olson, D.D. Allred, M.B. Squires, D. Markos, C.E. Mills, R.T. Turley, Brigham Young University

A neutral particle detector is being planned to orbit Mars as part of the ASPERA mission. It is designed to detect and classify atoms in the exosphere of Mars by their identity and velocity using a time-of-flight mass spectrometer. An electron released on collision with the first surface in the spectrometer (the start surface) initiates a start pulse for the spectrometer.

The most significant source of noise is thought to be UV photonsparticularly hydrogen Lyman alpha (121.6 nm), which are capable of generating false start and stop pulses. We have design using a genetic algorithm and fabricated a coating for the START surface which absorbs UV photons at 121.6 nm thus preventing their reaching the stop surface. The particular optical challenge was the fact that the particles and incident light arrives at an angle of 10 to 20 degrees from grazing. We will discuss the use of a genetic algorithm in designing the coating, its fabrication, AFM measurements of sample and at-wavelength measurements of their reflectivity.

10:20am **TF-ThM7 Studies of Pulsed DC Power in Magnetron Sputtering Systems**, *P.J. Kelly*, *J. O'Brien*, University of Salford, UK; *J.W. Bradley*, UMIST, UK, U.K.; *R. Hall*, *G. Roche*, Advanced Energy Industries Inc.; *R.D. Arnell*, University of Salford, UK

The application of pulsed DC power has proved to be highly advantageous in magnetron sputtering processes. Indeed, reactive pulsed magnetron sputtering is now amongst the leading techniques for the deposition of dielectric films. When the magnetron discharge is pulsed in the midfrequency range (20-350kHz), the periodic voltage reversals effectively discharge poisoned regions on the target. This significantly reduces the occurrence of arc events at the target and stabilises the deposition process. As a consequence, substantial improvements have been observed in film structure and properties, compared to films produced by continuous DC processing. More recently, interest has also focused on the effects which can arise when pulsed DC power is applied to the substrate. Pulsing the bias voltage appears to significantly increase the substrate ion current. For example, when compared to DC biasing, preliminary results have shown that a three-fold increase can be achieved in the current drawn at the substrate if the bias voltage is pulsed at 350kHz. However, despite these successes, aspects of this technology are not yet well understood. Consequently, detailed studies of the application of pulsed DC power, both to the magnetron and to the substrate, in a dual, variable field strength closed-field unbalanced magnetron sputtering system, are now in progress. Initial findings are reported here.

#### 10:40am TF-ThM8 Art and Science of Fabricating Optical Coatings by PECVD, L. Martinu, Ecole Polytechnique, Canada; D. Poitras, National Research Council of Canada, Canada INVITED

Low pressure plasma deposition using gas phase precursors is being increasingly used for the fabrication of dielectric optical films and coatings. This includes single-layer, multilayer, graded index and nanocomposite optical thin film systems for applications such as optical filters, antireflective coatings, optical waveguides and others. Besides their optical properties (refractive index, extinction coefficient, optical loss), these systems very frequently offer other desirable "functional" characteristics such as hardness, scratch-, abrasion- and wear resistance, adhesion to various technologically important substrate materials such as polymers, hydrophobicity or hydrophilicity, long-term chemical, thermal and environmental stability, and others. In this presentation, we review advances in the development of plasma processes and plasma systems, in the synthesis of high- and low index optical thin film materials, and in the control of plasma-surface interactions leading to desired film microstructures. We particularly underline the specific aspects of PECVD which are different from other conventional techniques used for optical films; this includes in particular fabrication of graded index (inhomogeneous) layers, high deposition rate, control of interfaces, enhanced mechanical and other functional characteristics, and industrial scale-up.

#### 11:20am **TF-ThM10 Inhomogeneous Optical Coatings Deposited by Plasma**, **D.** *Poitras*, National Research Council, Canada; L. Martinu, Ecole Polytechnique, Canada

Inhomogeneous optical coatings with a refractive index continuously varying with thickness appear to offer several attractive features from both fundamental and application points of view: (1) Understanding how accidentally-generated inhomogeneities can affect the optical performance of coatings can help to optimize the performance of optical filters; (2) purposely introduced and controlled optical inhomogeneities can be used to fabricate high performance inhomogeneous optical systems such as rugate filters; and (3) coatings with graded interfaces generally exhibit higher mechanical strength, better adhesion and good long term stability. In the present work, we studied these different aspects of inhomogeneous coatings produced by plasma enhanced chemical vapor deposition (PECVD). We used admittance diagrams (i) to interpret recent results concerning the effect of transition layers on the reflectance spectra of

homogeneous single films, and (ii) to derive an alternative explanation of specific properties of rugate filters. In addition, we describe a simple way for introducing the refractive index dispersion while designing rugate filters. The latter approach is documented by the performance analysis of complex refractive index profiles in a double band rugate filter and in a chirp mirror fabricated by PECVD.

11:40am **TF-ThM11 Uranium Coated Optics for Space Applications in the Extreme Ultraviolet**, *D.D. Allred*, *R.T. Turley*, Brigham Young University; *W.C. Cash*, University of Colorado; *M.B. Squires*, *D. Oliphant*, Brigham Young University

We have developed a new family EUV multilayer mirror coatings using uranium. Using this approach we have coated a set of 6 mirrors for the EUV Imager, a component of the IMAGE mission. It will study the distribution of He + in the Earth's plasmasphere by detecting its resonantly scattered emission at 30.4 nm (41 eV). The 30.4 nm feature is, in principle, relatively easy to measure because it is the brightest ion emission in the plasmasphere, it is spectrally isolated and the background at that wavelength is negligible. There is, however, a bright emission at 58.4 nm (21 eV) light, which comes from neutral helium in the earth's ionosphere which also must be blocked. It is at too high an energy to filter with aluminum but at too low an energy to have negligible reflectance from most materials commonly used in EUV mirrors. Thus, a multilayer system which satisfied two optical functions: high reflectance (>20%) at 41 eV but low reflectance (

### Thursday Afternoon, October 5, 2000

### Thin Films Room 203 - Session TF-ThA

### Transparent Optical Coatings

Moderator: J.R. Doyle, Macalester College

### 2:00pm TF-ThA1 Criteria for Choosing Transparent Conductors, R.G. Gordon, Harvard University INVITED

Transparent, electrically conductive films (TCOs) have been prepared from a wide variety of materials. These include oxides of tin, indium, zinc and cadmium, nitrides of titanium and chromium, and metals such as silver and gold. The physical properties of these materials are reviewed and compared. A figure of merit for a transparent conductor may be defined as the ratio of the electrical conductivity to the optical absorption coefficient of the film. The materials having the highest figures of merit are fluorinedoped zinc oxide and cadmium stannate. Physical, chemical and thermal durability, etchability, conductivity, plasma wavelength, work function, thickness, deposition temperature, uniformity, toxicity and cost are other factors that may also influence the choice of material for any particular application. The TCO materials are ranked according to each of these factors. The main applications of TCOs will be examined to see how these factors entered into the selection of the materials actually used.

### 2:40pm TF-ThA3 Preparation of Transparent Conducting Thin Films using Multicomponent Oxides Composed of ZnO and V@sub 2@O@sub 5@ by Magnetron Sputtering, *T. Miyata*, *S. Suzuki*, *H. Toda*, *T. Minami*, Kanazawa Institute of Technology, Japan

Recently, multicomponent oxides consisting of a combination of different binary or ternary compounds have recently attracted much attention as new transparent conducting oxide (TCO) materials. In this paper, we describe the preparation of TCO thin films using new multicomponent oxides of the ZnO-V@sub 2@O@sub 5@ system. Films were prepared on substrates at temperatures ranging from room temperature (RT) to 350@super o@C by conventional planar magnetron sputtering using powder mixtures of ZnO and V@sub 2@O@sub 5@ as the target. The carrier concentration of vanadium-doped ZnO (ZnO:V) films prepared using ZnOV@sub 2@O@sub 5@ targets markedly increased as the V@sub 2@O@sub 5@ content was increased from 0 to about 15 wt.%, whereas the Hall mobility decreased gradually. As a result, the resistivity of ZnO:V thin films reached a minimum at a V@sub 2@O@sub 5@ content of about 15 wt.%, and markedly increased with V@sub 2@O@sub 5@ contents above about 20 wt.%. Films prepared with V@sub 2@O@sub 5@ contents of about 50 to 70 wt.% were highly resistive or insulators and identified as a ternary compound, ZnV@sub 2@O@sub 4@. In contrast, the resistivity of films markedly decreased as the V@sub 2@O@sub 5@ content was increased from about 80 to 100 wt.%. A 100 wt.% vanadium oxide film with a thickness of 25 nm exhibited a resistivity of 5-10@super -4@@ohm@cm and an average transmittance above 70% in the visible range. In addition, this report describes the chemical properties and the impurity doping effect of TCO films using new multicomponent oxides of the ZnO- V@sub 2@O@sub 5@ system.

### 3:00pm TF-ThA4 Properties of Transparent conducting CdO-In@sub 2@O@sub 3@-SnO@sub 2@ Thin Films Prepared by Pulse Laser Deposition (PLD), *M. Yan*, *R.P.H. Chang*, *T.O. Mason*, *T.J. Marks*, *K.R. Poeppelmeier*, Northwestern University

Transparent conducting oxides (TCO) have extensive application in display devices, solar cells and sensing elements Various techniques have been applied to deposit TCO films including: thermal evaporation, sputtering, reactive ion plating, chemical vapor deposition (CVD), pulse laser deposition (PLD), atomic layer epitaxy (ALE), etc. The ternary alloy system of CdO-In@sub 2@O@sub 3@-SnO@sub 2@ has received much attention recently. Several compounds in this ternary systems, Cd@sub 2@SnO@sub 4@, CdIn@sub 2@O@sub 4@ and In@sub 4@Sn@sub 3@O@sub 12@, exhibit encouraging electrical and optical properties, while most of the ternary phase diagram (CdO, In@sub 2@O@sub 3@, SnO@sub 2@) remains unexplored. Furthermore, it is believed that there are some metastable phases and solution ranges not available in the bulk form but can be obtained as thin films. In our research, we synthesized and examined the electrical, optical and structural properties of thin films on Si and Corning 1737 substrates with different compositions deposited in a multi-target PLD system. Films were formed by first creating multi-layers of elemental oxides of CdO, In@sub 2@O@sub 3@ and SnO@sub 2@. The stoichiometry of the complex oxide was adjusted during this process. The

multi-layered films were then annealed in certain gas environment for a range of time and temperature to form polycrystalline ternary oxides. Preliminary results show that 5% In@sub 2@O@sub 3@ doped CdO has conductivity of 20,000S and bandgap of 2.75eV. Stoichiometric Cd@sub 2@SnO@sub 4@ has conductivity of 1600S and bandgap of 3.02eV. Stoichiometric CdIn@sub 2@O@sub 4@ has conductivity of 600S and bandgap of 3.05eV. When CdIn@sub 2@O@sub 4@ is doped with 5% SnO@sub 2@, its conductivity raised to 3,300S and its bandgap remains unchanged. It is believed that further improvements can be achieved through proper doping and annealing strategies.

3:20pm **TF-ThA5 Expanding Thermal Plasma Deposition of Natively Textured ZnO for Thin Film Solar Cell Applications**, *R. Groenen*, Eindhoven University of Technology, The Netherlands; *J. Loeffler*, Utrecht University, The Netherlands; *J.L. Linden*, TNO-TPD, The Netherlands; *R.E.I. Schropp*, Utrecht University, The Netherlands; *M.C.M. van de Sanden*, Eindhoven University of Technology, The Netherlands

A new approach for low temperature deposition of natively textured ZnO is developed, utilizing an expanding thermal argon plasma created with a cascaded arc. (Co)precursors are oxygen, diethylzinc and -additionally for doped films- trimethylaluminum, which undergo ionisation via charge exchange and consecutive dissociative recombination by respectively argon ions and electrons created in the arc. Films are deposited on Corning 1737 F glass at substrate temperatures of 200 - 350°C at a rate of 0.65 - 0.75 nm s@super -1@. The optical and electrical properties relevant for solar cell applications are comparable to those obtained for Asahi U-type SnO@sub 2@:F. Measurements of haze and angular resolved scattering intensity reveal increased light scattering with increasing deposition temperature and film thickness because of a rougher surface texture as confirmed by AFM and SEM measurements. In addition, virtually no loss in transmission of the ZnO films due to hydrogen plasma exposure is observed. In order to demonstrate the suitability for solar cell applications, p-i-n a-Si:H solar cells were co-deposited both on the natively textured low temperature material and Asahi U-type SnO@sub 2@:F, showing comparable efficiencies around 10%. The TCO / p-layer interface leads to effective light scattering, which results in high spectral response especially for long wavelengths.

### 3:40pm TF-ThA6 Effects of Excess Oxygen Introduced during Sputter Deposition and Post Annealing under a High Oxygen Pressure on Carrier Mobility in Indium-tin Oxide Films, *N. Kikuchi*, *E. Kusano*, *E. Kishio*, *A. Kinbara*, *H. Nanto*, Kanazawa Institute of Technology, Japan

Post-annealing for tin dope indium oxide films deposited at a low substrate temperature is sometimes needed to improve their optical properties. While the transparency in the visible range is enhanced by the annealing, the electrical conductivity of the film is deteriorated generally. The deterioration in the electrical conductivity is not only because of the reduction in carrier density, but also because of the reduction in carrier mobility. The reduction in the carrier mobility is thought to strongly relate to the introduction of excess oxygen into or on the film by the annealing. In this paper, indium tin oxide films with excess oxygen was prepared by deposition with a high oxygen concentration or by post-annealing under a high oxygen pressure in order to discuss its effects on electron mobility have been investigated. ITO films were deposited on glass substrates by r.f. sputtering under various oxygen concentrations in the discharge gas (0.3-100 %). Substrate temperature was kept at 773 K during deposition. Single phase of In@sub 2@O@sub 3@ was observed for all films deposited. A minimum resistivity of 1.8x10@super -4@ @ohm@cm was obtained for a film with a Sn concentration of 8 wt%, deposited at an O@sub 2@ concentration in the discharge gas of 0.3 %. With increasing oxygen concentration in the discharge gas from 0.3 % to 100 %, the Hall mobility decreased from 45 cm@super 2@V@super -1@s@super -1@ to 27 cm@super 2@V@super 1@s@super -1@ and the carrier density decreased from 1.0x10@super 21@ cm@super -3@ to 1.0x10@super 19@ cm@super -3@. By the post-annealing at 473 K for 30 min. in air, the Hall mobility of 27 cm@super 2@V@super -1@s@super -1@ increased to 37 cm@super 2@V@super -1@s@super -1@ and the carrier density of 1.0x10@super 19@ cm@super -3@ increased to 2.0x10@super 19@ cm@super -3@. The similar behavior of the Hall mobility and carrier density was observed for an ITO film annealed in O@sub 3@. These increases in the Hall mobility and carrier density during a low temperature annealing is thought to relate to desorption of excess oxygen existed at grain boundaries or the surface of the films because the annealing temperature is too low to improve the film crystallinity further and because it is hard to assume the formation of oxygen vacancies under the condition of the annealing. The results obtained support the hypothesis that the

### Thursday Afternoon, October 5, 2000

oxygen introduced into grain boundaries or adsorbed at the surface of the films act as charge traps and carrier scattering centers.

4:00pm TF-ThA7 Preparation and Properties of Transparent Conductive Aluminum-doped Zinc Oxide Thin Films by Sol-Gel Process, *M. Alam, D. Cameron*, Dublin City University, Ireland

Recently, numerous electrically conductive oxides have been discovered and extensively investigated. Of these, indium tin oxide (ITO) and ZnO are well known for their transparency when made into thin films and are expected to find wide use as transparent electrodes for many devices, such as Electrochromic (ECDs), Liquid crystal displays (ELs) and solar cells. Zinc oxide is one of the most promising transparent conducting oxides currently under investigation. Zinc oxide holds considerable promise as an optically transparent conducting material due to its wide band gap ( $\sim$ 3.3 eV), its amenability to defect or impurity doping and other desirable properties such as low cost and non-toxicity. Thin films of transparent conducting zinc oxide have been prepared by a variety of techniques, such as sputtering. chemical vapor deposition, reactive evaporation, spray pyrolysis and more recently by sol-gel process. Amongst the different techniques available, the sol-gel method seems to be the most attractive one due to coating on the desired shape and area, easy control of the doping level, solution concentration and homogeneity without using expensive and complicated equipment when compared to other methods. Highly conductive and transparent aluminum-doped zinc oxide thin films have been prepared from the solution of zinc acetate and aluminum chloride in ethanol by solgel process. The effect of changing the aluminum-to-zinc ratio from 0 to 6 at. % and annealing temperature from 0 to 600°C in vacuum has been thoroughly investigated. As-deposited films have high resistivity and high optical transmission. Annealing of the as-deposited films in vacuum leads to a substantial reduction in resistivity without affecting the optical transmission. The films have a minimum value of resistivity of about 1.5x10@super-3@ ohm-cm for 0.8 at. % aluminum-doped zinc oxide and a visible transmission of about 90%

#### 4:20pm TF-ThA8 Synthesis and Characterization of TCO Cobalt-Nickel Spinel Films, C.F. Windisch, Jr., K. Ferris, G.J. Exarhos, Pacific Northwest National Laboratory

Cobalt-nickel oxide films of nominal 100 nm thickness, and resistivities on the order of 0.01 ohm-cm have been prepared by spin-casting from both aqueous and organic precursor solutions followed by annealing at 450 C in air. Films deposited on sapphire substrates exhibit a refractive index of about 1.7 and are relatively transparent in the wavelength region from 600 to 8000 nm. They are also magnetic. The electrical and spectroscopic properties of the oxides have been studied as a function of Co/Ni ratio. An increase in film resistivity was found upon substitution of other cations (Zn@super 2+@, Al@super 3+@) for Ni in the spinel structure. However, some improvement in the mechanical properties of the films resulted. Conducting films also have been prepared upon substitution of cobalt by palladium. A combination of XRD, XPS, UV/Vis and Raman spectroscopy indicated that NiCo@sub 2@O@sub 4@ is the primary conducting component and that the conductivity is maximum at this stoichiometry. When Co/Ni < 2, NiO forms leading to an increase in resistivity; when Co/Ni > 2, the oxide was all spinel but the increased Co content lowered the conductivity. The influence of cation charge state and site occupancy in the spinel structure markedly affects calculated electron band structures and likely influences an anomalous switch of p-type conductivity to n-type conductivity seen at a Co/Ni ratio of 2. Electronic structure modeling studies also suggest the important role of the Ni@super +3@ cation in the conductivity mechanism. Finally, Raman spectra of the films were relatively easy to obtain and therefore were useful as a routine tool for identifying composition and optimizing conductivity.

#### 4:40pm TF-ThA9 Effect of Vacuum Deposited Polymer Substrate Roughness on ITO Electrical and Optical Properties, *M.A. Roehrig, C.I. Bright,* Presstek, Inc.

Increasing interest in next generation flexible flat panel display (FPD) materials and substrates has spurred research into improved/optimized ITO thin films deposited on polymer substrates. Requirements for FPD on flexible substrate are such that high conductivity and optical transmittance must be achieved for very thin ITO thin films, e.g. d@sub ITO@ - 5 nm to 100nm. At these thicknesses, polymer substrate roughness is expected to effect optical and electrical performance of the deposited ITO films making it difficult to achieve the high quality FPD requirements. An organic material vacuum deposition technique with the ability to control polymer film thickness from a few 10's of nanometers to several microns has been combined with ITO deposition from both ceramic (90% In@sub 2@O@sub

3@/ 10% SnO@sub 2@) and metal (90% In/ 10% Sn) targets. The effects of vacuum deposited polymer layer thickness and surface roughness effects on the electrical and optical properties of ITO thin films have been measured. Visible range optical performance, surface profilometry and electrical conductivity measurements, including carrier concentrations and mobilities, have been correlated with the vacuum deposited polymer layer thickness and surface roughness measurements.

5:00pm TF-ThA10 Properties of Sol-Gel Prepared (ZnO)@sub y@(CdO)@sub 1-y@ Thin Films, with Low Concentrations of Cd in Solution, C.I. Zúñiga-Romero, G. Torres-Delgado, L. Licea-Jiménez, S. Jiménez-Sandoval, O. Jiménez-Sandoval, R. Castanedo-Pérez, Unidad Querétaro, Mexico

(ZnO)@sub y@(CdO)@sub 1-y@ thin films were prepared by the sol-gel method, with low atomic concentrations (x) of Cd in solution, i.e. 0@<=@x@<=@0.32, at @Delta@x = 0.04 intervals. The precursor solution was mainly based on zinc acetate dihydrate, cadmium acetate dihydrate, and ethylene glycol. The films were deposited on slide glass substrates, and annealed at 400°C, in open atmosphere for 60 min. The X-ray diffraction data show that the films are formed by a polycrystalline mixture of wurzite-type ZnO and cubic-type CdO; the patterns, as well as electron dispersion spectroscopy (EDS) data, are indicative of a larger concentration (y) of CdO in the films, i.e. 0@<=@y@<=@0.7, with respect to that in solution. In support, the resistivity of the films decreases from @rho@=10@super 2@@ohm@cm for x = 0 (y = 0), to @rho@=5 x 10@super -2@@ohm@cm for x = 0.32 (y = 0.7). The UV-Vis spectra show that the films, throughout the composition range, display a high transmission, above 90%, at @lambda@==@600 nm.

### Friday Morning, October 6, 2000

### Thin Films Room 203 - Session TF+NS-FrM

#### **Nanostructured Thin Films**

Moderator: A. Hosseini-Tehrani, Florida International University

### 8:20am TF+NS-FrM1 Cluster Beam Synthesis of Nanostructured Thin Films, P. Milani, P. Piseri, E. Barborini, A. Podesta', C. Lenardi, Universita' Di Milano, Italy INVITED

We will present and discuss the use of supersonic cluster beam deposition (SCBD) for the production of nanostructured thin films. With this technique nanostructured films of refractory and semiconductor materials can be produced over large areas on various substrates at room temperature. Elemental building blocks are clusters with a number of atoms ranging from few tens up to few hundreds. These units organize in the film in hierarchical structures from the nanoscale to the mesoscale. By exploiting aerodynamical effects typical of supersonic beams it is possible to obtain very high deposition rates with a control on neutral cluster mass distribution, allowing the deposition of thin films with controlled nanostructure. Due to high deposition rates, high lateral resolution, low temperature processing SCBD can also be used for the micro and nanopattering of cluster-assembled films when little or no post-growth manipulation or assembly is required. As a practical example we will discuss the case of nanostructured carbon films. Surface morphologies, granularity and atomic structure of nanostructured carbon films grown with different precursors and under different conditions have been investigated by different techniques. The application of nanostructured carbon for the fabrication of supercapacitors and field emission devices will be discussed.

### 9:00am TF+NS-FrM3 Growth of Regular Arrays of Pillars and Helices with Repeat Distance Below 100 nm, *M. Malac*, University of Alberta, Canada; *R. Egerton*, Portland State University

Oblique deposition onto a rotating substrate pre-patterned with suitable nuclei results in the growth of regular arrays of pillars or helices.@footnote 1@ The repeat distance of such arrays can be varied from below 20 nm to over one micrometer. To improve the control over the microstructure it is beneficial to understand the growth mechanism on a microscopic scale. We find that the helices and pillars (within regular or random-nucleated arrays) are composed of many fibers growing simultaneously. The helix-arm diameter is determined by the number of fibers it contains. The distribution of fiber diameters is very narrow and remains constant along the entire helix height. The fiber-diameter, which is characteristic for given material and ratio of substrate and melting point temperatures, is in the order of a few nanometers. The crystalline nature of the growing material has only a minor influence on the fiber diameter. Additionally, we find that the columns formed within a film deposited onto a stationary oblique substrate are also composed of many individual fibers. The helix- and pillarsize distribution is much narrower within a regular unpatterned (randomly nucleated) array. This can be attributed to regularity of the shadowing between structures within a regular array. Anisotropy of shadowing within a regular square array arises from the varying distance of shadow-providing neighbors as substrate is rotated. This anisotropy has only a minor influence on the final shape of the pillars or helices. The helices within a random array start growth from a single fiber and exhibit a very narrow size distribution before the onset of bifurcation. This narrow sizedistribution was observed when the helix arm diameter (= fiber diameter) the lower limit of below scaling of the thin-film microstructure.@footnote 2@ @FootnoteText@ @Footnote 1@Malac M, Egerton RF, Brett MJ, Dick B, J. Vac. Sci. Technol. B 17 (6), 1999 @Footnote 2@Bales GS, Bruinsma R, Eklund EA, Karunasiri RPU, Rudnick J, Zangwill A, Science 249 (1990).

#### 9:20am **TF+NS-FrM4 Plasma Spray Deposition of Nanostructured Materials, H.M. Meyer, III,** R. White, Oak Ridge National Laboratory; T.T. *Meek*, University of Tennessee

Minimum film thickness achieved with any thermal-spray deposition process is limited by the size of powder feedstock materials. However, nanosized feedstock powder materials can be problematic for current plasma spray gun technology because of agglomeration and gun clogging. Some successes with nanopowder feedstock have been achieved, but mainly using special hardware and low quantities of expensive powders. We report the formation of nanostructured (i.e. nanomaterials) thin films using a unique combination of thermal spray coating techniques and liquid feedstock injection. This advanced thermal spray coating technology is a new method of synthesizing materials tailored at the nanoscale level. Injection of liquids into an arc-plasma gun offers the possibility of forming ultra-thin films at high deposition rates, a long-standing technology goal for the plasma spray industry. The formation of alumina thin films via plasma spray deposition using an aqueous precursor is presented. We compare the properties of our films with films formed by conventional thermal spray deposition using standard commercial alumina powders. Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR2272.

#### 9:40am TF+NS-FrM5 Deposition of Nanoparticles on Metal Surfaces, R.S. Averback, University of Illinois at Urbana-Champaign; J.M. Gibson, Argonne National Laboratory; K. Albe, C. Zimmermann, Y. Ashkenazy, M. Yeadon, University of Illinois at Urbana-Champaign INVITED

The deposition of metallic nanoparticles on surfaces has been investigated by a combination of molecular dynamics computer simulations and in situ transmission electron microscopy. It was observed that the reaction kinetics were dominated by a combination of interfacial stresses associated with epitaxy and capillary forces deriving from surface roughness. For Cu and Ag nanoparticles, it was found that the interfacial stresses led to 'contact epitaxy,' whereby the first few layers of the nanoparticles came into registry with the Cu(100) surface. Below a critical size, about 4 nm, the entire nanoparticle became epitaxial. For Co nanoparticles, which are more refractory and do not wet Cu(100) and Ag(100), contact epitaxy was not observed, although for deposition at 500 K, the nanoparticles burrowed into the substrate to achieve smoothing and coherency. Additional work examined how nanoparticles and grains in thin films respond to applied stresses. It will be shown that small particles on surfaces slide with little friction when they form a high energy grain boundaries, but that they quickly reorient during sliding and become locked from additional motion.

## 10:20am TF+NS-FrM7 Scanning Probe Investigations of Passivated and Bare Au Nanoclusters on H:Si(111), M.D.R. Taylor, P. Moriarty, University of Nottingham, UK; M. Brust, University of Liverpool, UK

Non-contact atomic force microscopy (NC-AFM) and scanning tunnelling microscopy (STM) have been used to characterise the morphology of thin films of decanethiol-capped 6 nm Au clusters spin-coated onto hydrogenpassivated (HF/NH4F treated) Si(111). Prior to cluster deposition, NC-AFM images taken under ambient conditions reveal that the H:Si(111) surface is atomically flat, typically consisting of 30-50 nm wide terraces separated by a mixture of single and multiple atomic steps. Following deposition of passivated clusters onto H:Si(111), a network of branched, dendritic islands (6 nm high) is observed with NC-AFM. The clousters forming these islands are remarkably loosely bound and may be swept aside by the AFM tip to fom agglomerates of clusters via minor modification of the non-contact mode feedback parameters. The underlying layers consist of poorly ordered clusters which are stable under STM imaging conditions with tunnel currentsup to 5 nA. This stability faciltates photon emission STM investigations of the passivated clusters. The results of comparative studies of STM-induced light emission from passivated and bare clusters (and from evaporated Au films) will be presented.

#### 10:40am TF+NS-FrM8 Nanophase Metal - Metal Oxide Films Deposited from a High-rate, Nanoparticle Beam, F.K. Urban III, A. Hosseini-Tehrani, P.D. Griffiths, A. Khabari, Florida International University; Y.-W. Kim, I. Petrov, L. Wei, University of Illinois

While interest in nanophase films deposited in vacuum from nanoparticle beams dates back to the early 1970s, development of suitable sources for such beams has been difficult. A rapidly increasing number of different materials are now being used to deposit nanophase films, from a few tenths to a micrometer in thickness. The new method employs DC magnetron sputtering and condensation of a conductive target material into a helium and argon gas mixture in a flow rate ratio of up to 0.12 at total pressures between 0.7-0.8 Torr. A low velocity beam of the gas and nanoparticles is formed as they escape through a 3 mm-diameter converging-diverging exit nozzle consecutively into differentially pumped chambers maintained at pressures less than 10-3 and less than 10-4 Torr, respectively. Results to date confirm a typically oxygen-containing nanophase film structure. A set of new metal and doped semiconductor elements including Ag, Al, Au, Co, Cr, Cu, Fe, Mo, Nb, Ni, Pt, Si, Sn, Ta, W, and Zr have just been deposited. To our knowledge, some of these are deposited in vacuum for the first time and details on their nanostructure, composition, and materials properties are just now being learned and will be reported. To date, all films are nanocrystalline with grain sizes ranging from 1 to 20 nm and have a porous structure metallic densities,

### Friday Morning, October 6, 2000

determined from combined Rutherford backscattering and film thickness measurements, in the range of 15-80% of the bulk densities. The effects of synthesis chamber wall cooling and gas conditions as well as starting material vapor pressure, melting point, and condensation energies will be presented. New findings on material properties will also be presented.

#### 11:00am TF+NS-FrM9 Thin Film Growth on a Fullerene Molecule, T.P. Martin, Max Planck Institut FKF, Germany INVITED

Since the surface of a fullerene molecule is not unlike that of graphite, it might be expected that they have similar properties when acting as a substate for thin film growth. The film-substrate interaction is indeed similar. However, the fact that the fullerene surface is curved and closes on itself leads to interesting differences. Both the similarities and the differences will be discussed including wetting, atom-packing, and reaction between film and substrate.

### 11:40am TF+NS-FrM11 Sputtered Fabrication of Periodic Sub-Micron Structures, B. Dick, M.J. Brett, University of Alberta, Canada

It is known that Glancing Angle Deposition (GLAD) utilizing extreme selfshadowing during film growth can produce periodic microstructures on a pre-defined seed layer with electron beam evaporation.@footnote 1@ This deposition process has been applied to the fabrication of periodic magnetic pillars and has proposed application in optical devices. However, because individual seed elements enforce adatom shadowing on the substrate surface, higher operating pressures, resulting in larger angular flux distributions, can be tolerated in the formation of GLAD microstructures when deposited on a seed lattice. In this presentation, we report the use of low-pressure sputter deposition to fabricate periodic GLAD microstructures of between 500nm and 1.5µm thickness on substrates patterned with a 500nm period seed layer. We have characterized the growth of the microstructures in terms of the target area, deposition pressure, throwdistance, and flux incidence angle. The use of sputtering for periodic GLAD simplifies the process control, and should enable deposition of a broader range of materials for diverse applications including magnetics, optics, and sensors. @FootnoteText@ @footnote 1@B. Dick, M.J. Brett, T.J. Smy, M.R. Freeman, M. Malac, R.F. Egerton. J. Vac. Sci. Technol. A. 18(4), 2000.

### **Author Index**

- A -Ahn, T.-H.: TF-TuP35, 15 Aita, C.R.: TF-TuA7, 9 Aivazov, A.A.: TF-TuP28, 14 Alam, M.: TF-ThA7, 26 Albe, K.: TF+NS-FrM5, 27 Allain, J.P.: PS1+TF+SE-ThM2, 21 Allred, D.D.: TF-ThM11, 24; TF-ThM6, 23 Anderson, S.L.: TF-WeM6, 17 Antinsh, A.: TF-TuP9, 11 Aoi, Y.: TF-TuP19, 12 Argoitia, A.: TF-ThM2, 23 Arnell, R.D.: TF-ThM7, 24 Ashkenazy, Y.: TF+NS-FrM5, 27 Averback, R.S.: TF+NS-FrM5, 27 Aydil, E.S.: PS1+TF+SE-ThM5, 21 — B — Babayan, S.E.: TF-TuP38, 16 Babcock, J.R.: TF-MoM5, 4 Barborini, E.: TF+NS-FrM1, 27 Barnett, S.A.: SE+TF-MoM6, 1; SE+TF-MoM7, 2 Bartelt, N.C.: SS2+NS+TF-MoM3, 2 Beauchamp, W.T.: TF-ThM2, 23 Behm, R.J.: SS2+NS+TF-MoM5, 2 Bello, I.: TF-TuP18, 12; TF-TuP29, 14 Berdnikov, A.A.: TF-TuP28, 14 Berg, S.: TF-TuA6, 8 Bermudez, V.M.: TF+EL-WeA9, 20 Bloomer, I.: TF-ThM5, 23 Bloomfield, M.O.: TF-WeM7, 17 Boo, J.-H.: TF-TuP12, 11 Boogaarts, M.G.H.: PS1+TF+SE-ThM6, 22 Böttcher, A.: TF+EL-WeA4, 19 Boyd, K.J.: TF-WeM6, 17 Bradley, J.W.: TF-ThM7, 24 Bray, K.R.: PS1+TF+SE-ThM3, 21 Brett, M.J.: TF+NS-FrM11, 28; TF-ThM3, 23; TF-TuM9.6 Brianso, M.-C.: TF-TuP26, 13 Bright, C.I.: TF-ThA9, 26 Brunner, H.: SE+TF-MoM1, 1 Brust, M.: TF+NS-FrM7, 27 Budaguan, B.G.: TF-TuP28, 14 - C -Cale, T.S.: TF-WeM7, 17; TF-WeM8, 18 Cameron, D.: TF-ThA7, 26 Carlotti, G.: TF-TuP33, 15 Cash, W.C.: TF-ThM11, 24 Castanedo-Pérez, R.: TF-ThA10, 26 Chae, H.-Y.: TF-TuP12, 11 Chan, C.Y.: TF-TuP29, 14 Chang, C.S.: TF-WeM5, 17 Chang, R.P.H.: TF-MoM5, 4; TF-ThA4, 25 Chang, S.H.: TF-WeM5, 17 Chao, B.S.: TF-TuP25, 13 Chen, L.J.: TF-WeM5, 17 Chen, W.: SS2+NS+TF-MoM7, 3 Chernomordic, V.D.: TF-TuP28, 14 Chiang, S.: SS2+NS+TF-MoM3, 2 Choi, B.-Y.: SS2+NS+TF-MoM2, 2 Chuang, R.: TF-TuP31, 14 Coburn, J.W.: TF-MoA7, 5 Cole, D.: PS1+TF+SE-ThM10, 22 Collins, R.W.: TF+EL-WeA7, 20 Conrad, H.: TF+EL-WeA4, 19 Cruden, B.A.: TF+EL-WeA2, 19 Cruz, M.P.: TF-TuP16, 12 — D · Dautzenberg, J.H.: TF-TuP7, 10 DeSisto, W.J.: TF+EL-WeA9, 20 Dick, B.: TF+NS-FrM11, 28 Ding, G.: TF-TuP38, 16 Doh, T.H.: TF-MoM8, 4 Author Index

Bold page numbers indicate presenter Doyle, J.R.: PS1+TF+SE-ThM10, 22 — F — Egerton, R.: TF+NS-FrM3, 27 Ektessabi, A.M.: TF-TuP1, 10 Elam, J.W.: TF-MoA3, 5; TF-MoM7, 4 Engelmark, F.: TF-TuA6, 8 Erwin, S.C.: SS2+NS+TF-MoM4, 2 Exarhos, G.J.: TF-ThA8, 26 — F — Fan, W.: TF-ThM4, 23 Ferguson, J.D.: TF-MoM3, 3 Ferris, K.: TF-ThA8, 26 Ferro, S.J.: TF-MoA3, 5; TF-MoM3, 3 Fouquet, P.: TF+EL-WeA1, 19 Franke, E.B.: TF-ThM1, 23 Fraser, D.: TF-MoA7, 5 Frederick, B.G.: TF-TuP34, 15 Fujiu, M.: TF-MoM4, 3 Fukarek, W.: TF+EL-WeA5, 19 Fung, M.K.: TF-TuP29, 14 — G — Gao, C.: TF-TuA9, 9 Gendron, F.: TF-TuP26, 13 George, S.M.: TF-MoA3, 5; TF-MoM3, 3; TF-MoM7, 4 Ghoranneviss, M.: SE+TF-MoM8, 2 Gibson, J.M.: TF+NS-FrM5, 27 Gitis, N.: TF-TuA9, 9 Gleason, K.K.: TF+EL-WeA2, 19 Goldner, R.B.: TF-TuP32, 15 González-Hernández, J.: TF-TuP25, 13; TF-TuP36, 15 Gorbulin, G.L.: TF-TuP28, 14 Gordon, R.G.: TF-ThA1, 25 Gorobets, Y.I.: TF-TuP36, 15 Grabarczyk, J.: TF-TuP27, 14 Granier, A.: PS1+TF+SE-ThM1, 21 Graves, D.B.: TF-MoA7, 5; TF-WeM4, 17 Greene, J.E.: TF-TuM1, 6 Greer, F.: TF-MoA7, 5 Griffiths, P.D.: TF+NS-FrM8, 27 Groenen, R.: TF-ThA5, 25 Groner, M.D.: TF-MoM7, 4 Grubbs, R.K.: TF-MoA3, 5 Gupta, A.: PS1+TF+SE-ThM3, 21 Guyot, M.: TF-TuP26, 13 — H — Haas, T.: TF-TuP32, 15 Hajek, V.: TF-ThM2, 23 Hale, J.S.: TF-ThM1, 23 Hall, R.: TF-ThM7, 24 Hamdi, M.: TF-TuP1, **10** Harrison, D.: TF-ThM5, 23 Hedge, P.: SE+TF-MoM7, 2 Hegemann, D.: SE+TF-MoM1, 1 Hicks, R.F.: TF-TuP38, 16 Hippler, R.: TF-TuP5, 10 Hoefnagels, J.P.M.: PS1+TF+SE-ThM6, 22 Hopster, H.: TF-TuP31, 14 Horiike, Y.: TF-TuP37, 15 Hosseini-Tehrani, A.: TF+NS-FrM8, 27 Houston, J.E.: TF-TuA1, 8 Hsu, S.T.: TF-TuP24, 13 Huang, R.F.: TF-TuP29, 14 Hubicka, Z.: TF-TuP4, 10 Hwang, R.Q.: SS2+NS+TF-MoM3, 2 -1lanno, N.J.: TF-TuP4, 10 Ichinohe, T.: TF-TuP21, 13 Inspektor, A.: SE+TF-MoM7, 2 Iriarte, G.F.: TF-TuA6, 8 Ito, N.: TF-TuP6, 10 — J — Jang, Y.C.: TF-TuP23, 13

Jansen, F.: TF-TuM11, 6 Jedrzejowski, P.: TF-TuP27, 14 Jeon, H.: TF-MoM8, 4 Jezl, M.L.: PS1+TF+SE-ThM11, 22 Ji, J.: SE+TF-MoM6, 1; SE+TF-MoM7, 2 Ji, Y.: TF-WeM3, 17 Jiménez-Sandoval, O.: TF-ThA10, 26 Jiménez-Sandoval, S.: TF-ThA10, 26 Joo, M.-S.: TF-TuP35, 15 Jung, D.-Y.: TF-TuP12, 11 — К — Kabashin, A.: TF-TuP3, 10 Kahng, S.-J.: SS2+NS+TF-MoM2, 2 Kamijo, E.: TF-TuP19, 12 Kang, B.-C.: TF-TuP12, 11 Kang, S.-K.: TF-TuP35, 15 Karim, Z.: TF-ThM4, 23 Katardjiev, I.V.: TF-TuA6, 8 Kawasaki, K.: TF-TuP21, 13 Keller, N.: TF-TuP26, 13 Kelly, P.J.: TF-ThM7, 24 Kenik, E.A.: TF-TuP34, 15 Kennedy, S.R.: TF-ThM3, 23 Kenny, J.M.: TF-TuP33, 15 Kessels, W.M.M.: PS1+TF+SE-ThM6, 22 Khabari, A.: TF+NS-FrM8, 27 Kidder, J.N.: TF-MoA1, 5 Kikuchi, N.: TF-ThA6, 25; TF-TuA3, 8 Kikuma, T.: TF-TuP10, **11** Kim, B.J.: TF-TuP7, 10 Kim, I.: SE+TF-MoM7, 2 Kim, K.S.: TF-TuP23, 13 Kim, Y.D.: TF-MoM8, 4 Kim, Y.-W.: TF+NS-FrM8, 27 Kinbara, A.: TF-ThA6, 25; TF-TuA3, 8 Kinoshita, H.: TF-TuP8, 11 Kishio, E.: TF-ThA6, 25 Klaus, J.W.: TF-MoA3, 5 Klemberg-Sapieha, J.E.: TF-ThM2, 23; TF-TuP17, 12; TF-TuP27, 14 Ko, D.-H.: TF-TuP35, 15 Koo, J.H.: TF-MoM8, 4 Kostylev, S.A.: TF-TuP36, 15 Koutzaki, S.H.: SE+TF-MoM2, 1; TF-TuP30, 14 Kozlovsky, L.V.: TF-TuP9, 11 Krenzer, B.: TF+EL-WeA4, 19 Krzanowski, J.E.: SE+TF-MoM2, 1; TF-TuA5, 8; TF-TuP30, 14 Kuk, Y.: SS2+NS+TF-MoM2, 2 Kusano, E.: TF-ThA6, 25; TF-TuA3, 8 -L-Lad, R.J.: TF-TuP34, 15 Lai, K.H.: TF-TuP29, 14 Lam, J.: TF-ThM5, 23 Lapicki, A.: TF-WeM6, 17 Latreche, M.: TF-ThM2, 23 Le Brizoual, L.: PS1+TF+SE-ThM1, 21 Lee, C.C.: TF-TuP31, 14 Lee, C.S.: TF-TuP18, 12; TF-TuP29, 14 Lee, J.-H.: TF-TuP12, 11 Lee, J.W.: TF-MoM8, 4 Lee, K.-C.: TF-TuP35, 15 Lee, K.W.: TF-TuP14, 11 Lee, M.-H.: TF+EL-WeA3, 19 Lee, N.-E.: TF-TuP23, 13 Lee, S.-B.: TF-TuP12, 11 Lee, S.T.: TF-TuP18, 12; TF-TuP29, 14 Lee, T.L.: TF-TuP15, 12 LeGore, L.J.: TF-TuP34, 15 Lenardi, C.: TF+NS-FrM1, 27 Leonelli, R.: TF-TuP3, 10 Letourneur, K.Y.: TF+EL-WeA8, 20 Li, N.: PS1+TF+SE-ThM2, 21 Li, Q.: TF-TuP18, 12

Licea-Jiménez, L.: TF-ThA10, 26 Lieber, C.M.: TF-TuM3, 6 Likhachev, D.V.: TF-ThM5, 23 Lin, C.C.: TF-TuP15, 12 Lin, J.H.: TF-TuP15, 12 Linden, J.L.: TF-ThA5, 25 Liu, X.W.: TF-TuP15, 12 Loeffler, J.: TF-ThA5, 25 Lozzi, L.: TF-TuP33, 15 Lucovsky, G.: TF-TuM7, 6 -M-Maa, J.S.: TF-TuP24, 13 MacWilliams, K.: TF-ThM4, 23 Madan, A.: SE+TF-MoM6, 1; SE+TF-MoM7, 2 Madey, T.E.: SS2+NS+TF-MoM7, 3 Magocsi, B.: PS1+TF+SE-ThM10, 22 Malac, M.: TF+NS-FrM3, 27 Mariotto, G.: TF-TuP33, 15 Markos, D.: TF-ThM6, 23 Marks, T.J.: TF-MoM5, 4; TF-ThA4, 25 Maroudas, D.: PS1+TF+SE-ThM5, 21 Martin, K: SE+TF-MoM7, 2 Martin, T.P.: TF+NS-FrM9, 28 Martinu, L.: TF-ThM10, 24; TF-ThM2, 23; TF-ThM8, 24; TF-TuP17, 12; TF-TuP27, 14 Masaki, S.: TF-TuP21, 13 Mason, T.O.: TF-ThA4, 25 Matsuura, T.: TF-MoM4, 3 McGahan, W.A.: TF-TuP22, 13 Meek, T.T.: TF+NS-FrM4, 27 Meichsner, J.: PS1+TF+SE-ThM7, 22 Meier, M.: PS1+TF+SE-ThM9, 22 Mendoza-Galván, A.: TF-TuP25, 13; TF-TuP36. 15 Messier, R.: TF+EL-WeA7, 20 Meunier, M.: TF-TuP3, 10 Meyer, III, H.M.: TF+NS-FrM4, 27 Milani, P.: TF+NS-FrM1, 27 Mills, C.E.: TF-ThM6, 23 Minami, T.: TF-ThA3, 25 Mitura, S.: TF-TuP27, 14 Miyata, T.: TF-ThA3, 25 Morales-Sánchez, E.: TF-TuP36, 15 Moriarty, P.: TF+NS-FrM7, 27 Morisaki, H.: TF-TuP21, 13 Muralt, P.: TF-TuA6, 8 Murota, J.: TF-MoM4, 3 -N-Nainaparampil, J.J.: TF-TuA10, 9; TF-TuA5, 8 Nainaparampril, J.: SE+TF-MoM2, 1 Nanto, H.: TF-ThA6, 25; TF-TuA3, 8 Nelson, C.E.: TF-MoA3, 5 Ni, J.: TF-MoM5, 4 Niedzielski, P.: TF-TuP27, 14 Niehus, H.: TF+EL-WeA4, 19 Norman, J.E.: PS1+TF+SE-ThM2, 21 Nowling, G.: TF-TuP38, 16 Nozaki, S.: TF-TuP21, 13 - o -O'Brien, J.: TF-ThM7, 24 Oehr, C.: SE+TF-MoM1, 1 Ogawa, H.: TF-TuP37, 15 Oh, S.-H.: TF-TuP35, 15 Ohuchi, F.S.: TF+EL-WeA3, 19 Ohwaki, T.: TF-TuP11, 11 Oliphant, D.: TF-ThM11, 24 Olson, S.: TF-ThM6, 23 Ono, K.: TF-TuP19, 12 Ono, Y.: TF-TuP24, 13 Ottosson, M.: TF-TuA6, 8 Ozolins, V.: SS2+NS+TF-MoM3, 2 — P — Pan, C.: TF-MoA5, 5 Paranjpe, A.: PS1+TF+SE-ThM2, 21 Parchamy Aragy, H.: SE+TF-MoM8, 2

### Author Index

Park, C.-G.: TF-TuP35, 15 Park, C.Y.: TF-TuP14, 11 Park, J.-Y.: SS2+NS+TF-MoM2, 2 Parsons, G.N.: PS1+TF+SE-ThM3, 21 Pashkevich, V.: TF-TuP9, 11 Pearsall, T.P.: TF-MoA1, 5 Petrov, I.: TF+NS-FrM8, 27 Phani, A.R.: SE+TF-MoM2, 1; TF-TuA5, 8 Phelps, R.C.: TF-MoA2, 5 Piseri, P.: TF+NS-FrM1, 27 Podesta', A.: TF+NS-FrM1, 27 Poeppelmeier, K.R.: TF-ThA4, 25 Poitras, D.: TF-ThM10, 24; TF-ThM8, 24 Popova, E.: TF-TuP26, 13 Portelles, J.J.: TF-TuP16, 12 Pribil, G.K.: TF-TuP4, 10 Prokhorov, E.F.: TF-TuP36, 15 - Q -Quaas, M.: TF-TuP5, 10 Quade, A.: TF-TuP13, 11 — R — Rabalais, J.W.: TF-WeM1, 17 Ramalingam, S.: PS1+TF+SE-ThM5, 21 Ramos-Mendoza, A.: TF-TuP25, 13 Richards, D.F.: TF-WeM7, 17 Riedel, R.: SE+TF-MoM1, 1 Ring, K.: TF-ThM4, 23 Ritala, M.K.: TF-MoM1, 3 Roche, G.: TF-ThM7, 24 Roehrig, M.A.: TF-ThA9, 26 Rogers, J.W.: TF-MoA1, 5 Roh, K.: TF-TuA4, 8; TF-TuP23, 13 Roh, Y.: TF-TuA4, 8; TF-TuP23, 13 Rossnagel, S.M.: TF-MoA5, 5 Rousseau, A.: PS1+TF+SE-ThM1, 21 Ruzic, D.N.: PS1+TF+SE-ThM2, 21 Sakayama, K.: TF-TuP19, 12 Sakuraba, M.: TF-MoM4, 3 Sakurada, K.: TF-TuP19, 12 Santucci, S.: TF-TuP33, 15 Sasaki, M.: TF-TuP19, 12 Satake, K.: TF-WeM4, 17 Sato, D.: TF-TuP6, 10 Sawin, H.H.: TF+EL-WeA2, 19 Scheffler, M.: SS2+NS+TF-MoM4, 2 Schmid, A.K.: SS2+NS+TF-MoM3, 2 Schowalter, L.J.: SS2+NS+TF-MoM8, 3 Schram, D.C.: PS1+TF+SE-ThM4, 21; PS1+TF+SE-ThM6, 22; TF+EL-WeA10, 20 Schropp, R.E.I.: TF-ThA5, 25 Schubert, M.: TF-ThM1, 23 Seaward, K.L.: PS1+TF+SE-ThM11, 22 Sedghi, A.: SE+TF-MoM8, 2 Seidel, T.: TF-MoA2, 5 Sen, S.: TF-WeM7, 17 Seo, J.W.: TF-TuP14, 11 Sherchenkov, A.A.: TF-TuP28, 14 Sherman, A.: TF-MoA5, 5 Shigesato, Y.: TF-TuP6, 10 Shih, H.C.: TF-TuP15, 12 Shokohi, A.: SE+TF-MoM8, 2 Shusterman, Y.V.: SS2+NS+TF-MoM8, 3 Sinnott, S.B.: TF-WeM3, 17 Sigueiros, J.M.: TF-TuP16, 12 Sit, J.C.: TF-ThM3, 23 Smets, A.H.M.: PS1+TF+SE-ThM4, 21 Sneh, O.: TF-MoA2, 5 Socino, G.: TF-TuP33, 15 Song, P.K.: TF-TuP6, 10 Soukane, S.: TF-WeM8, 18 Soukup, R.J.: TF-TuP4, 10 Sproul, W.D.: SE+TF-MoM3, 1 Squires, M.B.: TF-ThM11, 24; TF-ThM6, 23 Sriraman, S.: PS1+TF+SE-ThM5, 21

Steffen, H.: TF-TuP5, 10 Stenzel, W.: TF+EL-WeA4, 19 Su, W.B.: TF-WeM5, 17 Suzuki, S.: TF-ThA3, 25 — т — Tabet, M.F.: TF-TuP22, 13 Taga, Y.: TF-TuP11, 11 Tait, R.N.: TF-TuP20, 12 Taniguchi, K.: TF-TuP37, 15 Taylor, M.D.R.: TF+NS-FrM7, 27 Tessier, M.: TF-TuP26, 13 Thayer, G.E.: SS2+NS+TF-MoM3, 2 Tian, J.: TF-ThM4, 23 Toda, H.: TF-ThA3, 25 Tominaga, K.: TF-TuP10, 11 Torres-Delgado, G.: TF-ThA10, 26 Tosi, P.: TF-TuP33, 15 Tototzintle-Huitle, H.: TF-TuP25, 13 Trimble, C.L.: TF-ThM1, 23 Tsai, C.S.: TF-TuP31, 14 Tsai, Y.Y.: TF-TuP15, 12 Tsong, TienT.: TF-WeM5, 17 Tsuda, K.: TF-TuA3, 8 Turley, R.T.: TF-ThM11, 24; TF-ThM6, 23 Turner, F.: TF-MoA5, 5 — U — Urban III, F.K.: TF+NS-FrM8, 27 - v -Valentini, L.: TF-TuP33, 15 van de Sanden, M.C.M.: PS1+TF+SE-ThM4, 21; PS1+TF+SE-ThM6, 22; TF+EL-WeA10, 20; TF+EL-WeA8, 20; TF-ThA5, 25 van Hest, M.F.A.M: TF+EL-WeA10, 20 Vereda, F.: TF-TuP32, 15 Vernhes, R.: TF-TuP17, 12 Vetelino, J.F.: TF-TuP34, 15 von Keudell, A.: PS1+TF+SE-ThM9, 22; TF+EL-WeA8, 20 Vorobiev, Yu.V.: TF-TuP36, 15 - w -Wang, Y.: TF-ThM4, 23 Wei, C.M.: TF-WeM5, 17 Wei, L.: TF+NS-FrM8, 27 Westwood, W.D.: TF-TuM5, 6 White, R.: TF+NS-FrM4, 27 Windisch, Jr., C.F.: TF-ThA8, 26 Witte, G.: TF+EL-WeA1, 19 Wong, S.P.: TF-TuP29, 14 Woollam, J.A.: TF-ThM1, 23 Wu, Q.: SS2+NS+TF-MoM7, 3 Wu, W.: TF-TuP31, 14 Wulff, H.: TF-TuP13, 11; TF-TuP5, 10 - Y -Yakovlev, N.L.: SS2+NS+TF-MoM8, 3 Yan, M.: TF-MoM5, 4; TF-ThA4, 25 Yang, D.-Y.: TF-TuP35, 15 Yang, J.H.: TF-TuP14, 11 Yang, S.: TF-TuA4, 8; TF-TuP23, 13 Yeadon, M.: TF+NS-FrM5, 27 Yoo, H.J.: TF-TuP31, 14 Yoshida, M.: TF-TuP8, 11 Youn, S.: TF-TuA4, 8; TF-TuP23, 13 - Z -Zabeida, O.: TF-TuP17, 12 Zabinski, J.S.: TF-TuA10, 9 Zakharchenko, R.V.: TF-TuP36, 15 Zakharchenko, V.N.: TF-TuP36, 15 Zapien, J.A.: TF+EL-WeA7, 20 Zeng, X.: SE+TF-MoM5, 1 Zhang, F.: TF-TuP24, 13 Zhou, Z.F.: TF-TuP18, 12 Zimmermann, C.: TF+NS-FrM5, 27 Zúñiga-Romero, C.I.: TF-ThA10, 26

**Author Index**