

Nanometer Structures

Room 316 - Session NS-MoM

Quantum Dots and Nanoscale Devices

Moderator: E.T. Yu, University of California, San Diego

8:20am NS-MoM1 Conductance and Stability of Atom-sized Al Contacts under High Biases, J. Mizobata, Toshiba Corp., Japan; A. Fujii, S. Kurokawa, A. Sakai, Kyoto University, Japan

Single-atom contacts (SACs) of metals are known to exhibit various unique properties and considered to be a candidate of interconnects in nanoelectronics. In our previous experiments, we studied high-bias conductance of Au and Au-alloy SACs and showed that they can be observed up to 2 V. In order to know the maximum rating of other metal SACs, we carried out conductance measurements of Al SACs for biases from 0.1 to 0.8 V and investigated the formation and the lifetime of Al SACs as a function of the bias voltage. All measurements were made in UHV at room temperature on breaking Al pin-plate contacts, where SACs were observed just before their complete breakage. We found that the formation probability p_{Al} of Al SACs decreases with increasing the bias and leads to the suppression of the first peak in the conductance histogram. Both p_{Al} and the first peak vanish at around 0.8 V. On the other hand, the average lifetime of Al SACs, $\langle \tau_{\text{Al}} \rangle$, decreases almost linearly with increasing the bias but remains finite at 0.8 V. For comparison, we re-measured the high-bias conductance of Au SACs and found that p_{Au} and $\langle \tau_{\text{Au}} \rangle$ show similar bias dependence to that of p_{Al} and $\langle \tau_{\text{Al}} \rangle$, respectively, though the relevant bias range is much higher for Au SAC: p_{Au} , for example, survives up to 2.4 V. We consider that the reduction of p_{Au} and p_{Al} is due to a contact instability induced by electromigration, which fractures contacts in the middle of their deformation and hence reduces the chance of forming SACs. On the other hand, we found it difficult to explain the observed linear bias dependence of $\langle \tau_{\text{Al}} \rangle$ and $\langle \tau_{\text{Au}} \rangle$ by a simple rate theory since we know little about the effective contact temperature under high biases.

8:40am NS-MoM2 In-situ Monitoring of Quantum Conductance in Electrodeposited Magnetic Point Contacts@footnote 1@, C.-S. Yang, J. Thiltges, B. Doudin, University of Nebraska, Lincoln; M. Johnson, Naval Research Laboratory

The goal of our research is to investigate the magnetoresistance properties of magnetic quantum point contacts. A two-steps fabrication process is used. First, a 50 nm gap between two planar Au electrodes of 1-2 microns widths is patterned using focused ion beam milling. Second, a metallic film is slowly electrodeposited over the electrodes. In-situ measurements of the inter-electrodes impedance monitors the contact resistance during the growth. Keeping electrochemical control of the electrodes ensures optimum purity of the nanocontact, as well as the absence of oxides. Experiments are performed under sweeping magnetic field reaching 1600 Oe amplitude. Quantum conductance steps in Au and Ni point contacts are observed. For Ni, we find that an external field is helpful to observe quantum conductance in multiples of e^2/h , lifting the spin degeneracy. Opening and closure of nanocontacts seldomly occur during the magnetic field sweeping. No significant magnetoresistance was observed for samples of conductance values smaller than $50 e^2/h$. Optimizing the measurement speed, we show that no magnetoresistance values larger than 10 % occur when the resistance is stabilized at quantum plateau values during a few magnetic field sweeps. @FootnoteText@ @footnote 1@This research is supported by ONR and NSF MRSEC.

9:00am NS-MoM3 Quantum Dot Nucleation and Growth in a Microfluidic Reactor, T.L. Sounart, J.A. Voigt, T.A. Michalske, Sandia National Laboratories

Semiconductor quantum dots have the potential to transform important technologies including (bio-)chemical sensors, efficient light sources, catalysts, and supercapacitors. The current ability to control nanoparticle properties, however, is at a state of infancy. Quantum dots are synthesized in batch operations with no feedback and poor control of thermal, chemical, and fluid transport, resulting in a distribution of particle size and batch-to-batch variations. Microfluidic technology, which has revolutionized analytical chemistry and only more recently has been applied to chemical synthesis, offers numerous potential advantages over

existing techniques. It is expected that laminar flow, high heat transfer rates, and short mixing lengths can be exploited to precisely control crystal size and morphology, and that microreactor conditions can be adjusted instantaneously to tune output particle properties in real time. In addition to providing better control of reactor conditions, microfluidic systems provide a unique platform for investigation of fundamental reaction processes. Using optical measurement techniques, which are particularly suitable to quantum dot synthesis, we present here for the first time, an on-chip analysis of the nucleation and growth of nanoparticles. CdS early growth processes that are too fast to observe transiently have been resolved spatially in a continuous flow microreactor, and examined by imaging the fluorescence field in the microchannel upon excitation at 365 nm. Early results indicate, e.g., that cysteine-capped quantum dots are formed in less than a second of contact between Na_2S and CdSO_4 . We are currently analyzing the fluorescence field using hyperspectral imaging to extract data on particle size and concentration variations within the reactor for different chemistries and flow rates. This data is being incorporated into microreactor models to learn how to control quantum dot size and morphology.

9:20am NS-MoM4 Formation of 31P Qubit Test Structures by Single Ion Implantation, T. Schenkel, Lawrence Berkeley National Laboratory; J. Bokor, UC Berkeley and Lawrence Berkeley National Laboratory; D.H. Schneider, Lawrence Livermore National Laboratory; A. Persaud, Lawrence Berkeley National Laboratory; S.-J. Park, UC Berkeley and Lawrence Berkeley National Laboratory; J. Nilsson, Lawrence Livermore National Laboratory; J.A. Liddle, Lawrence Berkeley National Laboratory

Electron and nuclear spins of 31P atoms in silicon are promising candidates for the realization of a scalable solid state quantum computer architecture. Single ion implantation with low energy (<10 keV), highly charged ions offers a path to the formation of single 31P atom arrays. We describe our development of single ion placement technology and the integration of atom arrays with control gates and single electron transistor readout structures. Silicon nanowire based single electron transistors are formed in SOI (silicon on insulator) by electron beam lithography and stress limited oxidation. We will discuss critical process integration issues. @footnote 1@ @FootnoteText@ @footnote 1@ We thank the staff of the UC Berkeley Microlab for technical support. This work was supported by the National Security Agency and Advanced Research and Development Activity under Army Research Office contract number MOD707501, and by the U. S. Department of Energy under contract No. DE-AC03-76SF00098. Work at LLNL was performed under the auspices of the U. S. Department of Energy under contract No. W-7405-ENG-48.

9:40am NS-MoM5 Spin Based Qubit Fabrication in SiGe, L.J. Klein, K.A. Slinker, J.L. Truitt, M. Friesen, D.W. van der Weide, S.N. Coppersmith, R. Joynt, M.A. Eriksson, University of Wisconsin, Madison

A promising approach to solid-state implementation of quantum computers is electron spins in silicon devices. The design incorporates vertical and lateral tunneling into quantum dots defined by nanostructured top gates in the 2DEG of a strained Si quantum well. The potential in the two-dimensional electron gas is modulated by the voltages applied to the top metallic gates. Work is underway to fabricate quantum point contact and quantum dots in strained Si layer and quantum phenomena are investigated related to discrete charge variations. The ultimate goal is the fabrication of qubit: a quantum dot with single electron occupancy with a well defined spin state which is immune from decoherence. This scalable approach allows entanglement of two qubits by varying the voltage applied to top gates separating two quantum dots. Recent measurements of spin lifetime in strained SiGe structures shows decoherence times larger than micro seconds. This large decoherence time should allow many qubit logic operations, initialization, and read-out of a single spin qubit.

10:00am NS-MoM6 A Systematic Study of SiGe Quantum Fortresses and Possible Applications to Quantum Cellular Automata, T.E. Vandervelde, P. Kumar, T. Kobayashi, J.L. Gray, T.L. Parnell, R. Hull, J.C. Bean, University of Virginia

In this study we detail conditions that result in the generation and evolution of novel hetero-epitaxial surface structures in SiGe/Si created either by spontaneous self-assembly or by ion beam seeding. These self-assembled structures strongly resemble the proposed parameters for a Quantum Cellular Automata (QCA) unit cell. Specifically, we define the growth conditions (i.e. temperature, epi-layer thickness, Ge concentration, and growth rate) under which self-assembly of strain-stabilized quantum fortresses (QFs) and their precursors form. This growth progression can be dissected into a series of surface features that evolve before and after the

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appearance QFs. These kinetically limited configurations exist over a wide range of growth conditions, however they are destabilized by excessive adatom surface mobility or strain relaxation resulting from the introduction of misfit dislocations. To characterize these self-assembled structures and their destabilization, we have systematically studied and are basing simulations on their basic dimensional parameters, within this functional space. One natural application would be to use QFs in QCA based architectures. A fully developed QCA circuit requires arrays of QF-like structures, but nature only provides us with isolated randomly located QFs. To overcome this limitation we also report work directed at a guided self-assembly technique that relies on gently altering the substrate before growth. This is achieved using a 25 KeV in-situ Ga⁺ focused ion beam to locally enhance Ga⁺ concentration and alter the substrate's surface topography. The intent is to use the surfactant-like nature of low Ga doses, to cause local nucleation of Ge clusters without greatly disturbing surface topology. We also explore the effects of higher Ga⁺ dosages, which cause the appearance of significant surface topology, on the localization of Ge cluster nucleation. This work, in part, was supported by NSF through FRG and MRSEC grants.

10:20am NS-MoM7 Current Challenges in Nanocrystal-Quantum-Dot Lasing, V.I. Klimov, Los Alamos National Laboratory

INVT Semiconducting quantum dots (QDs) offer important advantages for lasing applications that are associated with their size controlled emission wavelengths (and, hence, output color) and low, temperature-insensitive optical-gain thresholds. QDs have been fabricated using epitaxial techniques (epitaxial or self-assembled QDs) or using chemical synthesis routes [nanocrystals or nanocrystal QDs (NQDs)]. Despite the impressive success of laser technologies based on epitaxial QDs, the first unambiguous demonstrations of amplified spontaneous emission¹ and lasing² involving chemically synthesized NQDs were performed only recently. The difficulties in achieving lasing in NQDs are due to both materials-quality issues and the existence of intrinsic physical mechanisms that complicate the development of stimulated emission. One such complication is ultrafast gain decay due to highly efficient, nonradiative, multi-particle Auger recombination. In our work we explore "geometrical" methods (e.g., nanocrystal shape control) for suppressing the multi-particle recombination. In particular, we study the effect of the zero- to one-dimensional (1D) transformation on Auger decay using series of elongated semiconductor nanocrystals (quantum rods). We observe an interesting new effect, namely, the transition from a three- to a two-particle recombination process as the nanocrystal aspect ratio is increased. This transition implies that in the limit of 1D confinement, Auger decay is dominated by Coulomb interactions between 1D excitons that recombine in a bimolecular fashion. One consequence of this effect is strongly reduced decay rates of higher order multi-particle states that lead to the increased optical gain lifetime and efficient light amplification due to excited-state transitions. These unique rod properties suggest that shape control may be key to developing practical lasing applications for nanocrystals. ¹V.I. Klimov et al., Science 290, 314 (2000). ²H.-J. Eisler et al., Appl. Phys. Lett. 80, 4614 (2002); M. Kazes et al., Adv. Mater 14, 317 (2002); A. Malko et al., Appl. Phys. Lett. 81, 1303 (2002).

11:00am NS-MoM9 Si Nanocrystal Synthesis in an Oxide Matrix: A Multiscale Computational Study, D. Yu, G.S. Hwang, University of Texas at Austin

Nanocrystalline Si (nc-Si) embedded in a SiO₂ matrix is receiving great attention due to its interesting fundamental physical properties and promising applications for advanced microelectronic devices and optoelectronic devices. The unique electrical and optical properties of embedded Si nanocrystals appear to be strongly influenced by their crystallite size, shape, density as well as Si/SiO₂ interface structures. It is therefore necessary to develop a detailed understanding of the nc-Si growth and Si-SiO₂ interfacial interactions. Although experiments offer many clues to the nanocrystal formation and interface properties, their interpretations often remain controversial. In this talk, we will present our multiscale computational model for the synthesis of Si nanoclusters in an oxide matrix. Our multiscale model integrates various state-of-the-art theoretical methods at different time and length scales, such as first principles quantum mechanics, molecular mechanics, and kinetic Monte Carlo. Using the multiscale approach, we have examined i) formation mechanism of Si clusters in silicon suboxide, ii) shape evolution of embedded nanoclusters, iii) Si-SiO₂ interface structure and strains. Our simulations show that small silicon clusters agglomerate very rapidly at the early stage of thermal annealing mostly via coalescence. As

the Si cluster density gets lower, the coalescence becomes less probable and the cluster growth continues mainly by Ostwald ripening (which appears be several orders of magnitude slower than the initial stage coalescence). Our theoretical study also demonstrates that the average size of silicon clusters is a strong function of the initial silicon supersaturation. Our results are in good agreement with recent experimental observations.

11:20am NS-MoM10 Nanocrystalline Structures in Amorphous Silica, J.Y. Cheng, Rensselaer Polytechnic Institute; M.M.J. Treacy, NEC Research Institute; P.J. Keblinski, Rensselaer Polytechnic Institute

We conduct the metamict transformation of crystalline silica in a transmission electron microscope. In this experiment, an alpha quartz crystal was transformed into an amorphous phase by electron irradiation at high dose. In the meantime, diffraction patterns of these phases were taken throughout the process. After that, we measured image fluctuations in dark field for the amorphous structure. From the images, the amorphous silica is "nanocrystalline." From the diffraction patterns, these crystallites are randomly oriented. Our results also show that the original alpha phase has ultimately disappeared in the new structure.

11:40am NS-MoM11 Investigation of Nucleation and Growth of Si(Ge) Nanocrystals Embedded in HfO₂ as Floating Gate for Flash Memory Devices, R. Gupta, National University of Singapore; L.K. Bera, Institute of Microelectronics, Singapore; W.J. Yoo, National University of Singapore, Singapore; D.S.H. Chan, National University of Singapore; N. Balasubramanian, Institute of Microelectronics, Singapore

Charge storage in semiconductor nanocrystals is a very critical property to determine electrical performance of non-volatile memory devices. Nanocrystals embedded in high dielectric constant materials are not only effective to scale down the device size but also to enhance the programming and retention properties. Also, it is known that Si(Ge) nanocrystals of size ≤ 10 nm can have much better charge storage capability at room temperature than Si nanocrystals. This study is focused on understanding mechanisms to control shape, size, and composition of Si(Ge) nanocrystals that will be used for improving device properties of non-volatile memories. The Si(Ge) nanocrystals were deposited using Silane & Germane at the pressures of 0.5Torr - 5Torr and at the temperatures of 500°C-600°C on 40Å of either thermally grown SiO₂ or MOCVD HfO₂. The deposition time was varied from 5 seconds to 70 seconds at different flow rates of Silane & Germane. It was found that the evolution of size and density of Si(Ge) nanocrystals was dependent on pressure, deposition time, and substrate material. We found, as the deposition pressure decreased from 5 Torr to 0.5 Torr, the minimum size of Si(Ge) nanocrystal on SiO₂ decreased from 50 nm to 2 nm while density increased from 10⁸/cm³ to 10¹¹/cm³. We observed that nanocrystal size increased in early stages but agglomeration took over with the further increase of deposition time. For SiO₂, we found that Ge atomic percent decreased from 18.4% to 14.6% as the deposition time increased from 5 seconds to 15 seconds at 5 Torr. However, Ge atomic percent on HfO₂ at same conditions at 5 seconds was lower at 12.3 %, showing significant difference in kinetics of the Si(Ge) nanocrystal formation between HfO₂ and SiO₂ substrates. Details on nucleation, growth, and electrical results on charge storage of Si(Ge) nanocrystals on HfO₂ will be presented.

Magnetic Interfaces and Nanostructures

Room 316 - Session MI+NS-TuM

Magnetic Imaging and Magnetic Spectroscopies

Moderator: G.D. Waddill, University of Missouri - Rolla

8:20am **MI+NS-TuM1 Characterization of Magnetic Thin Films and Nanostructures using Electron Microscopy, D.J. Smith**, Arizona State University **INVITED**

The reduced dimensions of magnetic thin films and nanostructures lead to major and often unexpected changes in magnetic properties and behavior. In addition to intrinsic scientific importance, these novel characteristics have obvious relevance to current and projected technological needs. Successful implementation of this technology requires a detailed understanding of materials growth mechanisms. Chemical and crystallographic structure must be correlated with micromagnetic structure and dynamic response before the fundamental limits of device performance can be firmly established. For example, atomic-level imaging and microanalysis of structural and chemical changes induced by changes in growth temperature or by post-deposition annealing are essential for explaining enhanced magnetic properties of antiferromagnetic pinning layers and magnetic tunnel junctions. And electron holography allows direct visualization of magnetization behavior within patterned nanostructures. This talk will provide an overview of electron microscopy and related techniques, with illustrative examples that demonstrate the major contributions being made to ongoing studies of magnetic thin films and nanostructures.

9:00am **MI+NS-TuM3 Imaging of Magnetic Nanoislands at the Thermal Stability Limit, M. Bode, O. Pietzsch, A. Kubetzka, R. Wiesendanger**, University of Hamburg, Germany

Within the past decade spin-polarized scanning tunneling microscopy (SP-STM) became a mature tool for high spatial resolution imaging of the static domain structure of ferro- and antiferromagnetic surfaces. Recently, we successfully observed the temperature-dependent switching behavior of Fe monolayer islands which were pseudomorphically grown on a Mo(110) substrate and exhibit an perpendicular easy axis. Our SP-STM results show that at temperatures between 15 and 26 K Fe islands consisting of 250-600 atoms (area 20-40 nm²) are superparamagnetic, i.e., they change their magnetization direction on a time scale of 0.1-1000 s. Small islands were found to switch more often than larger islands as can be expected on the basis of anisotropy barrier considerations. A quantitative analysis reveals, however, that the observed size-dependent variation of the switching rate is much larger than theoretically expected. Possible origins of this behavior are discussed in terms of the island shape and environment. @FootnoteText@ @footnote 1@ S. Heinze et al., Science 288, 1805 (2000). @footnote 2@ A. Wachowiak et al., Science 298, 577 (2002). @footnote 3@ M. Bode, Rep. Prog. Phys. 66, 523 (2003).

9:20am **MI+NS-TuM4 Scanning Tunneling Spectroscopy of Magnetic Impurities at Metal Surfaces, M.A. Schneider**, Max Planck Institute for Solid State Research, Germany **INVITED**

A single magnetic impurity in a metal host is a paradigm of many-body physics in electronic systems. The spin-flip scattering of host electrons at the impurity site leads to the formation of a correlated electron state, the Kondo state. Only recently has it become possible to study this state using Scanning Tunneling Spectroscopy (STS) for magnetic surface impurities. @footnote 1-5@ Through this method, magnetism and properties of the adsorbate-host interaction can be determined in a local, atomic-scale measurement. The Kondo state is characterized by the formation of a resonance at the Fermi energy, which allows to access the characteristic energy scale, the Kondo temperature T_K of the system. We discuss the properties of the Kondo state created by the interaction of the magnetic atom with surface and bulk electrons, and the role of the tunneling process in the appearance of the resonance in STS spectra. The interaction of the magnetic impurity with two-dimensional surface-state electrons is demonstrated by the measurement of a resonant scattering phase-shift for Co adsorbed on Ag(111). @footnote 4@ However, this interaction with surface-state electrons is only weak, the main properties of the Kondo state are determined by the interaction with bulk electrons. This is corroborated by experiments comparing Co impurities on various Cu surfaces where the decisive role of the number of interaction channels to bulk electrons in the atomic-scale system is shown. @footnote

5@. @FootnoteText@ @footnote 1@ J.-T. Li, W.-D. Schneider, R. Berndt, B. Delley, Phys. Rev. Lett. 80, 2893(1998). @footnote 2@ V. Madhavan, W. Chen, T. Jamneala, M. F. Crommie, N. S. Wingreen, Science 280, 567 (1998). @footnote 3@ H.C. Manoharan, C. Lutz, D. M. Eigler, Nature 403, 512 (2000). @footnote 4@ M. A. Schneider, L. Vitali, N. Knorr, K. Kern, Phys. Rev. B 65, 121406(R) (2002). @footnote 5@ N. Knorr, M. A. Schneider, L. Diekhöner, P. Wahl, K. Kern, Phys. Rev. Lett. 88, 096804 (2002).

10:00am **MI+NS-TuM6 A Practical Guide to the Interpretation of Point-contact Andreev Reflection Data, R.J. Soulen, G.W. Woods, I. Mazin, M. Osofsky**, Naval Research Laboratory

Point-contact Andreev reflection (PCAR), has become a useful tool in determining the spin polarization, P , of magnetic materials. It consists of establishing a point contact between a sharpened superconductive point and a magnetic base (or, vice versa), and measuring the conductance G of the junction as a function of the applied voltage, V . The value of P can be extracted from the conductance data through use of a modified Blonder, Tinkham, Klapwijk (BTK) model of the supercurrent conversion at the superconductor-metal interface (Andreev reflection). This algorithm, however, does not take into account several factors which depend on properties of the point contact: whether it is in the ballistic or diffuse regime, ratio of the spreading resistance to the junction resistance, the value of the superconducting energy gap. These properties are often difficult to measure or estimate so that the practitioner is left without a means to assess the error in the value of P . We have systematically examined these effects (by theory and experiment) and can offer some new and practical guidance on how to correct for them and to estimate the error. We use data on several materials (CrO₂, SrRuO₃, and LaSrMnO₃) taken in our laboratory and in others to illustrate the process.

10:20am **MI+NS-TuM7 Preparation and Magneto-Optical Spectroscopic Studies of Diluted Magnetic Semiconductor Quantum Dots and Related Nanostructures: Potential Building Blocks for Spintronics Applications, D.R. Gamelin, D.A. Schwartz, P.V. Radovanovic, N.S. Norberg, J.D. Bryan**, University of Washington **INVITED**

Diluted magnetic semiconductors (DMSs) are currently the focus of intense applications-oriented research in the emerging area of spin-based electronics, or "spintronics." DMS nanostructures such as quantum dots (DMS-QDs), quantum wells, quantum wires, and epitaxial thin films are pivotal architectural elements in many proposed spintronics devices including spin-dependent LEDs, field-effect transistors, and quantum computers. A central challenge facing the development of this technology is the identification of semiconductors that combine the necessary properties of conductivity and ferromagnetic ordering at temperatures above room temperature. This seminar will present our group's recent advances in the development of direct routes for preparation of freestanding high-quality DMS quantum dots. Emphasis will be placed on the application of magneto-optical spectroscopic methods (including magnetic circular dichroism and Zeeman spectroscopies) to study the electronic structural properties of these materials. Spectroscopic identification of ligand field, charge transfer, and excitonic transitions in DMSs will be presented in the context of their functional properties. The use of variable-temperature variable-field magneto-optical methods to define ground state spin-orbit splittings, and the influence of such splittings on the magnitudes of semiconductor band level Zeeman splittings, will also be discussed.

11:00am **MI+NS-TuM9 Magnetic Linear and Circular X-ray Dichroism Studies of the Magnetic Instability of Fe(x)Ni(1-x) Pseudomorphic Thin Films Exhibiting the Invar Effect, S.A. Morton**, Lawrence Berkeley National Laboratory; M. Hochstrasser, Lawrence Livermore National Laboratory; N.A.R. Gilman, R.F. Willis, Pennsylvania State University; G.D. Waddill, University of Missouri - Rolla; J.G. Tobin, Lawrence Livermore National Laboratory

At a composition of 65% Fe, bulk Fe(x)Ni(1-x) alloys exhibit the invar effect: a sudden change in the atomic volume which is associated with a dramatic change in the magnetic ordering from a high-spin high-volume state to a low-spin low-volume state at higher Fe concentrations; this results in a collapse in the magnetic moment and Curie temperature. Magnetic X-ray Linear Dichroism measurements of the Fe and Ni 3p exchange splitting have been used as a probe of the element specific Fe and Ni magnetic moments for ultra thin fcc FeNi/Cu(100) films across the full compositional range. These results have been further complemented by composition dependent Magnetic X-ray Circular Dichroism measurements of the element specific orbital and spin moment contributions. The data shows excellent agreement with published neutron and SQUID magnetometry

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measurements and with theoretical predictions of the Fe and Ni atomic moments based upon the 2 γ state model and the Slater Pauling Curve. Furthermore, the data demonstrate the potential for the use of magnetic linear dichroism as a quantitative element specific magnetometer in a wide variety of magnetic thin film systems.

11:20am **MI+NS-TuM10 Magnetic Circular X-ray Dichroism of Gd₂O₃ Nanoparticles**, *K. Uvdal, R.M. Petoral, Jr., F. Söderlind, P.-O. Käll*, Linköping University, Sweden

In this study we are investigating the possibilities to use magnetic circular X-ray dichroism (MCXD) to probe the magnetic properties of Gd₂O₃ nanoparticles. The Gd₂O₃ nano particles were further characterized by means of X-ray Photoelectron Spectroscopy (XPS) to investigate the elemental composition the nanoparticles as well as verifying the oxidation level. The particle size of Gd₂O₃ nanoparticles is estimated from Atomic Force Microscopy (AFM) and transmission electron microscopy (TEM). The elemental composition shows high carbon content, which is expected due to the synthesis pathway. The relative carbon content could be reduced by Ar sputtering of the Gd₂O₃ nano particles, in good agreement with earlier studies on CoO. MCXD is used to determine the orbital-to-spin relative magnetic moment. It is shown that the orbital-to-spin relative ratios are greatly enhanced for sputtered sample. Gd₂O₃ nanoparticles show a superparamagnetic behaviour at room temperature and a large orbital contribution to the magnetic moment at low temperature. MCXD is shown to be a powerful tool for investigating magnetic properties of small volume samples.

11:40am **MI+NS-TuM11 Magnetism in Transition-metal Alloy Films: Lineshape Analysis of Magnetic Linear Dichroism Angle-selective Photoemission Spectra**, *R.F. Willis, N.A.R. Janke-Gilman*, The Pennsylvania State University

MLD photoemission measurements using synchrotron radiation to excite atomic core levels are reported for thin epitaxial films of transition-metal binary alloys. Careful background subtraction gives spectral lineshapes which are analyzed to give information on the magnitudes of the elemental magnetic moments and the degree of local magnetic order. The width of the dichroism spectrum is shown to relate to the magnitude of the moment, while the amplitude reflects the local magnetic anisotropy and ordering. Dichroism spectral widths and amplitudes are plotted as a function of alloy composition, reflecting changing magnetic behavior. The elemental spectral widths track the Slater-Pauling curve showing changing moments as a function of changing composition. Changing spectral amplitudes are compared with neutron scattering results which show changing magnetic anisotropy and magnetic order. Measurements taken on Beamline 7.0.1 at the Advanced Light Source, Berkeley, CA.

Nanometer Structures Room 308 - Session NS-TuM

Nanowires

Moderator: D.G. Cahill, University of Illinois, Urbana-Champaign

8:20am **NS-TuM1 Growth and Characterization of Single-Crystal ZnO Nanowires**, *Z. Zhu, T. Chen, Y. Gu, G. Neumark, R.M. Osgood Jr.*, Columbia University

One-dimensional ZnO nanowires have attracted increasing interest for both fundamental and applied studies of short-wavelength optoelectronic nanodevices. This talk reports a systematic study of effect of the variation of growth parameters, including growth temperature, growth time and catalyst (Au) film thickness, in determining the collective and individual structure of ZnO nanowires. Our single-crystal ZnO nanowires were grown on different-orientation silicon and sapphire substrates via vapor-phase transport. The synthesized ZnO nanowires were characterized by scanning electron microscopy (SEM), X-ray diffraction (XRD), energy dispersive x-ray spectroscopy (EDS) and photoluminescence (PL) spectroscopy. Room-temperature photoluminescence spectra of the ZnO nanowires revealed a strong, narrow excitonic emission at ~ 380 nm and a very weak green emission band at ~ 508 nm. The full width at half maximum (FWHM) of the excitonic emission at ~ 380 nm was ~ 95 meV, indicating that the ZnO nanowires are of good optical quality. SEM measurements were made of ZnO nanowires grown on silicon substrates with Au films of different-coverage. The growth studies have shown that, as the Au-thin-film coverage decreases, the width and area density of the nanowires decreases while the length of the nanowires increases. In addition, the SEM

measurements of the ZnO nanowires, grown at different substrate temperatures, show that the spatial uniformity of ZnO nanowires is strongly dependent on substrate temperature. Strategies of manipulating the spatial orientation of ZnO nanowires for practical applications are being explored by using nanofabrication techniques such as electron-beam lithography to pattern the substrates and build blocks to confine the growth of the ZnO nanowires; these studies will be reported in this talk.

8:40am **NS-TuM2 Growth and Characterization of ZnO Nanowires**, *J.B. Baxter, E.S. Aydil*, University of California, Santa Barbara

ZnO is a wide band gap semiconductor with applications in UV optoelectronics, transparent conducting oxide coatings, piezoelectronics, and photovoltaics. Nanostructured ZnO can exhibit quantum confinement effects and enable applications requiring high surface area such as sensors and dye sensitized solar cells. We have grown monodisperse ZnO nanowires by chemical vapor deposition (CVD) using the organometallic precursor zinc acetylacetonate (Zn(acac)₂) in the presence of oxygen. Nanowire diameters depend on the growth conditions and range from 16 nm to 100 nm. The growth morphology depends sensitively on the substrate and the partial pressure of Zn(acac)₂. On a-plane sapphire, nanowires grow epitaxially and perpendicular to the substrate in dense arrays and with in-plane rotational order. X-ray diffraction pole figures confirm the epitaxial relationship ZnO(0001)||Al₂O₃(11-20) and ZnO(11-20)||Al₂O₃(10-14) epitaxy and the trigonal symmetry of the substrate. Controlled sublimation and delivery of the solid precursor is challenging. However, we are improving our ability to control nanowire growth by studying the evaporation and decomposition of Zn(acac)₂ using thermogravimetric analysis and mass spectrometry and by monitoring the presence of the Zn(acac)₂ with in situ Fourier transform infrared (FTIR) spectroscopy. Dense ZnO nanowires with high surface area can be grown on various oxide substrates, making them suitable for replacing the mesoporous semiconductor in dye sensitized solar cells. Single crystal ZnO nanowires offer improved conduction pathways compared to sintered nanoparticles used currently, where electron transport occurs by a hopping mechanism.

9:00am **NS-TuM3 Structure, Defect and Cathodoluminescence Studies of GaN Nanorods and Nanowires**, *L.C. Chen*, National Taiwan University, Taiwan; *C.S. Shen, S.C. Shi*, National Taiwan University; *S. Dhara, C.T. Wu, K.H. Chen*, Academia Sinica, Taiwan; *C.W. Hsu, C.C. Chen*, National Taiwan Normal University

Single-crystalline GaN and related 1D nanostructures, specifically, binary InN, AlN along with their ternary In_xGa_{1-x}N and In_xAl_{1-x}N counterparts have been successfully grown by catalytic chemical vapor deposition. Their structure and optical properties are investigated by scanning and transmission electron microscopy, Raman, photoluminescence (PL) as well as cathodoluminescence (CL) techniques. Diameter and position selective growth of these 1D nitride nanostructures has been demonstrated by pre-treatment of the substrate surface with size-controlled catalyst. Oriented growth of the nanorods was also obtained under hetero- or homo-epitaxial conditions. While PL measurements usually give spectral data from numerous nanowires and nanorods with a broad distribution of diameter, the CL measurements (from room temperature down to 4 K) can easily be performed on single nanowire or nanorod. A higher CL peak position of individual GaN nanorod than that of bulk GaN film was observed, indicating the presence of strain in the pristine nanorod, which is also confirmed by X-ray diffraction analyses. In addition, a blue shift of CL peak position with decreasing the diameter of GaN nanorod was noticed. However, the magnitude of the peak shift is much more pronounced than that estimated from quantum confinement. Finally, Ga³⁺ ions implantation of these GaN 1D nanostructures has been studied using 50-keV Ga³⁺ focused ion beam. Phase transformation and defect structure evolution as a function of irradiated ion-beam fluence is also investigated by electron-microscopy-based techniques.

9:20am **NS-TuM4 Onset of Nanowire Growth by Vapor-Liquid-Solid (VLS) Epitaxy**, *J.W. Dailey, J.L. Taraci, T. Michael, J.C. Thorp, S.T. Picraux*, Arizona State University

We report on CVD growth of Ge and Si nanowires on Si substrates by the Vapor Liquid Solid (VLS) technique. While many groups have formed random clusters of Si nanowires at high pressures by VLS, relatively little effort has been directed at the controlled CVD growth of epitaxial arrays of nanopillars or nanowires directly onto Si substrates. In our studies Au

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nanodots are formed by UHV evaporation on hydrogen terminated Si (100) and (111) substrates. Subsequent selective area growth is carried out using digermane or disilane at pressures from 1×10^{-2} to 1×10^{-5} T and temperatures from 400 to 600 C. At the lower pressures (representative of gas phase MBE) we observe the growth of Ge nanopillars that nucleate at the AuSi eutectic and grow vertically and laterally, undergoing coalescence as growth continues. RBS and ion channeling are used to establish the VLS substrate orientation and temperature dependent kinetics of the Ge nanopillar growth, and SEM elucidates the morphological evolution of the nanopillars. At pressures above 10^{-4} T we observe an abrupt change in the nature of the growth from a relatively slow nanopillar growth to a much more rapid nanowire growth. The nanowires are distinguished by long narrow axial growth structures with much slower lateral growth. The transition from nanopillar to nanowire growth is interpreted in terms of a nucleation-limited process. Due to the small lateral dimensions (10 to 50 nm) of these 3-D structures lateral strain relief is expected to occur and large lattice mismatches should be accommodated without defects, in contrast to large area heteroepitaxy. These CVD nanoscale structures could form the basis for new in situ synthesis of 3-D Si device structures on Si substrates.

9:40am **NS-TuM5 Functional Semiconductor Nanowires and Their Optical Properties**, *P. Yang*, University of California, Berkeley **INVITED**

Nanowires are of both fundamental and technological interest. They represent the critical components in the potential nanoscale electronic and photonic device applications. In this talk, I will introduce the vapor-liquid-solid crystal growth mechanism for the general synthesis of nanowires of different compositions, sizes, orientation and doping profile. Particularly, synthesis and organization of different types of heterostructured nanowires will be discussed. Wide band gap semiconductor nanostructures with near-cylindrical geometry and large dielectric constants exhibit two-dimensional ultraviolet and visible photonic confinement (i.e. waveguiding). Combined with optical gain, the waveguiding behavior facilitates highly directional lasing at room temperature in controlled-growth nanowires with suitable resonant feedback. The nanowire optical emission has been studied in detail using high-resolution optical microscopy. The waveguiding behavior of individual zinc oxide (ZnO, GaN) nanowires depends on the wavelength of the emitted light and the directional coupling of the photoluminescence (PL) to the emission dipoles of the nanowire. Pumping at high pulse intensity leads to the transition from spontaneous to stimulated emission, and analysis of the polarization, linewidth, and spacing of the spectral features facilitates identification of the transverse and longitudinal cavity modes and their gain properties. The observation of lasing action in arrayed and isolated ZnO/GaN nanowires without requiring fabrication of mirrors suggests the single-crystalline, well-faceted nanowires can indeed function as effective resonance cavities. This concept of using well-cleaved nanowires as natural optical cavities may be extendable to many other different semiconductor systems. @FootnoteText@ @footnote 1@ Y. Wu, R. Fan, P. Yang, Nanolett, 2, 83, 2002. @footnote 2@ M. Huang, S. Mao, H. Feick, H. Yan, Y. Wu, H. Kind, E. Weber, R. Russo, P. Yang, Science, 292, 1897, 2001. @footnote 3@ J. Johnson, H. J. Choi, K. P. Knutsen, R. D. Schaller, R. J. Saykally, P. Yang, Nature Materials, 1, 101, 2002. @footnote 4@ J. Johnson, H. Yan, R. Schaller, L. Haber, R. Saykally, P. Yang, J. Phys. Chem. B, 105, 11387, 2001.

10:20am **NS-TuM7 Mo@sub 3@Se@sub 3@ Nanowires - Mechanical and Electrical Properties at the Nanoscale**, *A. Heidelberg*, Trinity College Dublin, Ireland; *J.W. Schultze*, Heinrich-Heine-Universität Düsseldorf, Germany; *G. Staikov*, Forschungszentrum Jülich, Germany; *J.J. Boland*, Trinity College Dublin, Ireland

Low dimensional organic and inorganic materials like nanowires and nanotubes have attracted much interest as potential building blocks for nanotechnology. This interest can be traced to the novel structural and electronic properties of these materials. Here we describe a study that measures the electronic and mechanical properties of the inorganic polymer (LiMo@sub 3@Se@sub 3@)@sub n@ together with nanowire-networks that have been synthesized by exchanging the Li-counterion with different alkylammonium- and pyridinium-ligands. (LiMo@sub 3@Se@sub 3@)@sub n@ forms quasi-1D crystals and is structurally related to the Chevrel phases. It can be viewed as a condensation polymer of Mo@sub 3@Se@sub 3@ units. The crystals can be dissolved in polar solvents with @epsilon@ > 45. In these solvents the crystals disassemble into single nanowires with a diameter of 0.6 nm (from crystal data and TEM) and bundles of nanowires, depending on the solutions concentration. From solution, single nanowires, bundles of nanowires or films of nanowires can be cast on various substrates. Both, the wires themselves as well as the

nanowire films are highly conductive but susceptible to electrical degradation (oxidation) in air. The ion exchanged wires form self assembled networks with an inter-wire spacing determined by the length of the side chain of the alkylammonium- and pyridinium-ligands. Conductivity measurements on these nanowire networks at different temperatures and oxidation times show that conduction is activated and occurs via a percolation mechanism. The mechanical properties of single nanowires or bundles were studied using a SPM-nanomanipulator. This instrument allows us to controllably apply forces (μN - nN range) to supported Mo@sub 3@Se@sub 3@-nanowires to effect nanoscale manipulations. Using the lateral force data of the manipulations, the mechanical properties like Youngs modulus and tensile strength of the wires can be measured.

10:40am **NS-TuM8 Defect Mediated Electronic Transport in Nano and Molecular Wires**, *D.A. Bonnell*, *S. Kalinin*, *M. Freitag*, *A.T. Johnson*, University of Pennsylvania

Any rational approach to nanostructure design necessitates a fundamental understanding of the properties of the constituents, as well as collective behavior of ensembles. We have developed 2 new approaches to measuring local electromagnetic properties based on scanning probes that can be applied to nano and molecular wires, Scanning Impedance Microscopy and Nano Impedance Spectroscopy. These approaches access the frequency dependence of electronic transport over 3-6 orders of magnitude, depending on experimental conditions. The frequency dependence can be used to determine mechanisms of electronic transport, particularly the processes that occur at defects. We demonstrate this approach by determining the local electronic structures of individual defects in single walled carbon nanotubes. We then generalize to nanowires and molecular wires.

11:00am **NS-TuM9 Electronic Structure and Excited States of One-dimensional Polydiacetylene Nanowire**, *M. Akai-Kasaya*, *K. Shimizu*, *A. Saito*, *M. Aono*, *Y. Kuwahara*, Osaka University and SORST JST, Japan

The polydiacetylene (PDA) nanowire can be fabricated at designated positions by using a STM probe tip on a self-assembled monomolecular (SAM) layer. @footnote 1@ The fabricated PDA wire grows out in a straight line and extends to a sub-micrometer length on the surface. The fully extended conjugated backbone of the PDA is not only expected to function as an electrically conducting nanowire but is also interesting in terms of exploring physics in one-dimensional (1D) systems. In this work, the density of states of individual polymers and constituent monomers were studied by STS. The STS spectrum delineating the density of states of PDA wire clearly reveals the theoretically predicted @pi@-band and band edge singularities of the 1D conjugated polymer. We have also observed a fascinating spectrum with a narrow gap, which is suggested to be due to the existence of the charge-carrying polaron states on a polymer backbone. Furthermore, we demonstrated that an excited state took place in an isolated polymer nanowire following the polymerization. The voltage pulse initiates additive polymerization, which proceeds instantaneously to both sides of the monomer array on the SAM layer. Before and after polymerization within the disabled feedback loop, the tunneling current shows the accountable difference due to the steady-state current on the monomer and derived polymer, respectively. However, the anomalous current, which often continues for few hundred micro-seconds, has been observed simultaneously with inception of the polymerization. We have estimated statistically the time of onset and duration of the current and correlation with the length of the derived polymer wire. And then, it can be concluded that the detected anomalous current results from the vibrational excitation states of a derived molecular nanowire. These results are remarkable and interesting in terms of one molecular science. @FootnoteText@ @footnote 1@ Y. Okawa and M. Aono, Nature 409, 683 (2001).

11:20am **NS-TuM10 STM and DFT Study of Gadolinium Silicide on Si(100)**, *B.C. Harrison*, University of North Carolina at Chapel Hill, Ireland; *J.J. Boland*, Trinity College Dublin, Ireland

The fabrication and characterization of low-dimensional nanoscale structures is motivated by the desire to produce materials and devices with novel optical, structural, and electronic properties. Due to the difficulties in nanoscale fabrication by a top-down approach, self-assembly of nanoscale materials represent an attractive alternative. Rare earth silicide on the Si(100) surface is one such system that has attracted significant interest over the past several years. Nanostructures of various silicides@footnote 1,2,3@ have been formed with high aspect ratios, micrometer length scales, large mechanical strengths, and metallic character; all of which make them potential candidates for nanoscale interconnects or device

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components. However, these nanowires cannot be successfully used in electronic circuits until the morphology and placement of wires are controlled. This study focuses on Gadolinium Silicide (GdSi_2) on Si(100) since this silicide forms nanowires and has the smallest lattice constant mismatch in the wire growth direction of any of the available rare earth silicides at growth temperatures. Scanning Tunneling Microscopy data and DFT calculations results are coupled to determine the morphology of the various phases of GdSi_2 on the Si(100) surface. Furthermore, STM images are acquired from room temperature to wire-growth temperatures in order to study the atomic structure and growth processes of the initial wetting layer and nanowires themselves. At least three forms of the wetting layer and two forms of wires will be discussed in connection with an overall surface phase diagram for GdSi_2 on Si(100). @FootnoteText@@footnote 1@ Chen, Y.; Ohlberg, D. A. A.; Williams, S. J. Appl. Phys. 2002, 91, 3213.@footnote 2@ Chen, Y.; Ohlberg, D. A. A.; Medeiros-Riberio, G.; Chang, Y. A.; Williams, S. Appl. Phys. Lett. 2000, 76, 4004.@footnote 3@ Nogami, J.; Liu, B. Z.; Katkov, M. V.; Ohbuchi, C.; Birge, N. O. Phys. Rev. B 2001, 63, 233305-1.

11:40am **NS-TuM11 Theoretical Calculation of the Thermal Conductivity of Semiconducting Nanowires**, *N. Mingo, L. Yang*, NASA-Ames Research Center

An atomistic Green function theoretical formalism to compute phonon transport in nanostructures will be presented, and its application to several different problems will be discussed. In particular, we present calculations of the thermal conductivity of Si and Ge nanowires, and compare these with some experimental results [D. Li et al., submitted]. One important problem that has not yet been extensively studied in an atomistic framework, is that of ballistic vs. diffusive phonon transport. Using our atomistic Green function approach, we study the transition from ballistic to diffusive phonon transport, occurring as the system's length increases. The way in which this transition takes place is largely determined by properties of its boundary. We will discuss the ballistic-diffusive transition in terms of atomic properties of the wire and its coating. Differences between (111) and (110) orientated nanowires are shown to be of more importance in the ballistic regime than in the diffusive one. Finally, a two parameter model, with the parameters depending only on bulk material properties, is also derived. Using this method we obtained good predictive calculations of the thermal conductivity of Si nanowires. The method employs the full phonon dispersion relations of bulk Si. The relative importance of specific nanowire modes not present in bulk, as the system's size becomes smaller, will be discussed. The results and methods presented offer an exciting new range of possibilities in the study and development of thermal transport through nanosized devices.

Magnetic Interfaces and Nanostructures

Room 316 - Session MI+NS-TuA

Self Assembly and Nanomagnetism

Moderator: S.D. Bader, Argonne National Laboratory

2:00pm **MI+NS-TuA1 Many-spin Hamiltonian for the Single-molecule Magnet Mn12-Ac**, *K. Park*, Naval Research Laboratory and Howard University; *M.R. Pederson*, Naval Research Laboratory; *S.L. Richardson*, Howard University and Naval Research Laboratory

Nanoscale single-molecule magnets recently received great attention due to scientific and practical reasons: macroscopic quantum phenomena and possible utilization as magnetic storage devices or quantum computing. A single-molecule magnet (SMM) is a three-dimensional array of identical molecules, each of which consists of several transition metal ions surrounded by organic ligands and is independent of neighboring molecules. Among many kinds of SMMs, Mn12-Ac has been the most extensively studied for the past decade. Although the low-energy features of Mn12-Ac have been well understood by considering each molecule as an effective ground-state spin of $S=10$, there is still a big controversy over the energy gap between the first excited-state manifold and the ground-state manifold as well as the internal structure of the single molecule. To provide a guide to understanding the controversial many-spin features, we investigate the intramolecular exchange couplings and the projected single-ion anisotropies using density-functional theory (DFT). We use all-electron Gaussian-orbital-based Naval Research Laboratory Molecular Orbital Library (NRLMOL) within Perdew-Burke-Ernzerhof (PBE) generalized-gradient approximation (GGA). Based on the calculated exchange couplings and anisotropy parameters, we construct a model many-spin Hamiltonian which reproduces calculated single-spin results and allows for the extraction of many-spin features.

2:20pm **MI+NS-TuA2 Magnetic Interaction in Assemblies of Nanometer-sized Fe Dots on Cu (111)**, *M.A. Torija*, *J. Pierce*, University of Tennessee, Knoxville; *J.F. Wendelken*, Oak Ridge National Laboratory; *E.W. Plummer*, University of Tennessee, Knoxville; *J. Shen*, Oak Ridge National Laboratory

Assemblies of separated iron quantum dots can be prepared on the Cu(111) surface via a buffer-layer-assisted growth process. First, an inert Xe layer is frozen onto a Cu(111) substrate that is held below 30 K. Then, Fe atoms are dosed from a typical evaporation source and form clusters on the Xe layer. Finally, the sample is warmed above 90 K, allowing the buffer layer to evaporate and the formed quantum dots to land on the surface. Scanning tunneling microscopy has shown us that we can control the average spacing and size of the dots by changing the Xe layer thickness and/or the amount of Fe deposited. Surprisingly, the dot arrays show non-zero remanent magnetization that is stable with the passage of time. To distinguish the roles of the magnetic interactions vs. the magnetic anisotropy in stabilizing the remanent magnetization, measured by SMOKE, we compare the ordering temperature of dot assemblies that have equal size distribution but different density. At fixed dot size distribution, varying the density of the Fe dots from 0.003 to 0.015 leads to an enhancement of ordering temperature from 153 K to 363K. This clearly indicates that magnetic interactions play an important role in stabilizing the remanent magnetization. Another interesting phenomena that we observed is a spin reorientation induced by the dot size. that for a fixed nominal thickness, the easy axis of magnetization is perpendicular for lower Xe thickness (small dots), and becomes in-plane for higher Xe thickness (big dots). It may be explained by the interplay between surface and bulk anisotropies.

2:40pm **MI+NS-TuA3 Contribution of Orbital Magnetism to the Magnetism of Monodisperse Nanoparticles**, *M. Farle*, Universitaet Duisburg-Essen, Germany **INVITED**

Self-organized magnetic nanoparticles with diameters of less than 10 nm are interesting for technological applications and for the investigation of interface properties due to their high surface-to-volume atom ratio. One of the most important magnetic properties, the magnetic anisotropy energy (MAE) is strongly influenced by the local structure and size of the particles, since on the atomic level MAE is related to the anisotropy of the orbital magnetic moment. Well-known techniques to measure the orbital contribution to the total magnetic moment are ferro-/paramagnetic resonance (FMR/EPR) and x-ray magnetic circular dichroism. Two examples will be discussed: a) disordered 3 nm FePt with different Fe contents, b) 11.4 nm CoO@Co (a 2nm CoO shell surrounding a 8 nm Co core). For the FePt particles with different Fe concentration we find a linear increase of the g-

factor measured by FMR/EPR, i.e. of the ratio of orbital-to-spin magnetic moment for larger Pt contents. This indicates that the presence of Pt induces an enhanced orbital magnetic moment in the nanoparticle. In the case of CoO@Co we find by FMR a bulk-like g factor $g = 2.15$ of fcc Co, while XMCD yields a 300 % enhanced ratio of orbital-to-spin moment. A quantitative comparison taking the different sampling depths of both techniques into account reveals the presence of uncompensated large magnetic Co moments at the interface of the antiferromagnetic CoO shell to the ferromagnetic Co core. Supported by EC contract no. HPRN-CT-1999-00150 and Deutsche Forschungsgemeinschaft.

3:20pm **MI+NS-TuA5 Self-assembly of FePt Nanoparticles on Si(100) Surface**, *N. Shukla*, *J. Ahner*, *D. Weller*, Seagate Research

Chemically synthesized monodispersed FePt nanoparticles are of great interest due their high magnetic anisotropy. The self-assembly and uniform coating of these nanoparticles on substrates is crucial for enabling high-density magnetic recording media. We have studied various parameters, potentially influencing the uniformity of FePt nanoparticle coatings. In particular, we report on the effects of excess surfactant concentration, type of surfactant, solvents and substrates. Films are fabricated using dip-coating and spin-coating methods. A narrow range of surfactant concentration is identified that leads to long range ($\sim 1 \times 1 \text{ mm@super 2@}$) uniformity. Outside this concentration range the nanoparticle coatings form clusters with local self-assembly. In addition, the type of solvent and type of surfactant has a profound impact on the self-assembly of FePt. Decreasing the size of surfactant chain length changes the self-assembly from uniform to ring structures. Polarity and viscosity of the solvents also impact the self-assembly. Polar solvents give poor uniformity. Low viscous solvents have a similar impact.

3:40pm **MI+NS-TuA6 Submicron Cobalt Particle Fabrication by Ion Beam Induced Chemical Vapor Deposition (IBICVD)**, *Y. Kageyama*, *T. Suzuki*, Toyota Technological Institute, Japan

Nanometer-sized patterned structures for high density data storage have recently become of great interest. It has been demonstrated that the ion-beam induced chemical vapor deposition (IBICVD) technique has a potential benefit for fabrication of nano-dots. @footnote 1,2@ Characterization of IBICVD-synthesized Co particles was performed, and the result is presented in this paper. The submicron Co particles were deposited on Si@sub 3@N@sub 4@ substrates by a focused Ga@super +@ ion beam (FIB) system equipped with a source reservoir filled with precursor of octacarbonyl dicobalt [Co@sub 2@(CO)@sub 8@] powders. Vapor of the precursor was introduced through a feeding nozzle (0.5mm diameter) above the substrate separated by 0.5 mm. The base pressure of the deposition chamber was about 10@super -5@ Pa. The ion current and the pressure during deposition were 14 pA and 0.7 - 1.4 x 10@super -4@ Pa, respectively. The in-situ image of Co particles was taken by SEM of the FIB system. Under the condition of irradiation of ion beams, the particle formation process is rather complicated due to concurrence of competitive processes (etching and deposition), therefore the morphology of Co particles strongly depends on the ion beam dwell time (5 to 120 μs) and the partial pressure of Co@sub 2@(CO)@sub 8@ precursor, as revealed by AFM analysis. The smallest size of Co particle obtained is about 150 nm so far. They exhibit ferromagnetic behaviors. Further studies on modification of properties by heating substrates, and on formation of alloys by introducing a second deposition source, are in progress. @FootnoteText@@@footnote 1@ A. Lapicki, E. Ahmad, and T. Suzuki, J. Magn. Magn. Mat. 240 (2002) 47@footnote 2@ A. Lapicki, K. Kang, and T. Suzuki, IEEE Trans. Magns. 38 (2002) 2589.

4:00pm **MI+NS-TuA7 Magnetic Nanostructures Made by Self-assembled Block Copolymer Lithography**, *C.A. Ross*, *J.Y. Cheng*, *H.I. Smith*, *E.L. Thomas*, Massachusetts Institute of Technology; *G. Vancso*, University of Twente, The Netherlands **INVITED**

The fabrication and magnetic properties of thin-film particles with diameters of 35 nm and periodicity of 50 nm made using block copolymer nanolithography will be described. Such particle arrays may be used in magneto-electronic and magnetic storage devices, where it is important to control the magnetization state, switching field, and uniformity of the particles and to understand their size-dependent magnetic behavior. Arrays of single-layer Co and NiFe particles with thicknesses of 5, 10, 15 and 20 nm, and Co/Cu/NiFe multilayer particles have been made. The Co and NiFe particles show an increase in coercivity and a decrease in switching field distribution with thickness. The particles exhibit thermally-assisted reversal, with switching volumes larger than the physical particle volume due to strong magnetostatic coupling between the particles. The multilayer

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particles show hysteresis behavior consistent with interlayer magnetostatic coupling, and measurable giant magnetoresistance despite the small dimensions of the particles. These arrays have short-range close-packing, but no long-range order. To impose long-range order the substrates have been patterned with shallow grooves, which induce alignment of the rows of polymer features parallel to the steps creating an ordered array. The polymer domain spacing conforms to the dimensions of the templating features leading to a quantized number of rows of domains within each groove. It is also possible to confine the polymer to certain regions of the substrate using soft printing methods, which also leads to a limited degree of ordering. Results from these templated self-assembly processes will be discussed. This work was supported by NSF. Refs: Cheng et al, Adv. Mater. 13 1174 (2001); Appl. Phys. Letts. 81 3657 (2002); IEEE Trans. Magn. 38 2541 (2002).

4:40pm **MI+NS-TuA9 Magnetic Properties of Low-dimensional Nanostructures on an Insulator**, *Z. Gai, J.R. Thompson, J. Pierce, J. Shen*, Oak Ridge National Laboratory

Magnetic nanostructured materials are attracting much attention because of the dramatic changes in their magnetic, electronic and transport properties compared with conventional bulk materials. In previous work, iron zero-dimensional dots, one-dimensional nanowires and two-dimensional films have been successfully prepared on top of a commonly used insulating NaCl (001) single crystal surface. In-situ atomic force microscopy images show that the sizes of the dots and the widths of the wires are very uniform; the films are atomically flat and are formed due to a high nucleation density. In the present work, the magnetic properties of the dots, wires and films are measured by Superconducting Quantum Interference Device (SQUID) magnetometer X-ray magnetic circular dichroism (XMCD). The wires have an out-of-plane easy magnetization axis, and surprisingly show ferromagnetic stability even at room temperature. The magnetic behaviors of the dots and films are very different from the wires. The detailed comparison will be discussed in the talk. Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Dept. of Energy under contract DE-AC05-00OR22725.

5:00pm **MI+NS-TuA10 Magnetic Reversal of Co/Pd Multilayer Films and Sub-100nm Islands**, *G. Hu, T. Thomson, M.E. Best, B.D. Terris*, Hitachi San Jose Research Center; *C.T. Rettner, S. Raoux, G.M. McClelland, M.W. Hart*, IBM Almaden Research Center

Patterned arrays of Co/Pd multilayer islands with perpendicular anisotropy are one approach to increasing magnetic recording density towards 1Tbit/in². To realize this technology arrays consisting of single domain islands with sufficient anisotropy for thermal stability and a narrow switching field distribution will be required. In order to understand the reversal properties of islands we have compared the reversal mechanism and anisotropy of patterned arrays to nominally identical unpatterned, continuous films. The island arrays were fabricated by creating an etch mask using electron beam lithography and nano-imprinting followed by etching of a SiO₂ substrate. Multilayer films of Co/Pd were then sputter deposited onto the topographically patterned substrates. We found that for the continuous films, the magnetic anisotropy is only sensitive to the Co and Pd layer thicknesses while coercivity and magnetization reversal mechanism can be easily tuned by varying the deposition conditions. However, for small, single domain islands, the coercivity is much less sensitive to deposition conditions and more sensitive to composition than for the continuous films. The coercivity of these islands is generally significantly greater than that of the continuous films. Moreover, the switching behavior of the islands does not exhibit any correlation with the film reversal mechanism, but rather follows the film magnetic anisotropy closely. Systematic studies have been carried out to adjust the magnetic anisotropy of the multilayer films by varying the cobalt and palladium layer thicknesses. Unlike the continuous films, the measured coercivity of the islands agrees well with the reversal field calculated based on the measured anisotropy of the film and the Sharrock equation.

Tuesday Evening Poster Sessions, November 4, 2003

Nanometer Structures

Room Hall A-C - Session NS-TuP

Poster Session

NS-TuP1 Electrical Characteristics of Semiconductor-Atomic Superlattice for Silicon-on-Insulator Application, Y.-J. Seo, DAEBUL University, Korea; R. Tsu, University of North Carolina at Charlotte

Silicon on insulator (SOI) structure is a critical material for future ultra-large scale integration (ULSI). Recently, we had been reported that the Si-O superlattice can be serve as an epitaxially grown insulating layer as possible replacement of SOI. Up to a bias of 30 V, the field inside the multi-layer structure reaches $\sim 3 \times 10^7$ V/cm. There is no sign of breakdown. However, the low voltage isolation is not quite sufficient for implement as a substitute for silicon on insulator. In this paper, the monolayers of oxygen atoms sandwiched between the adjacent silicon layers formed by ultra high vacuum-chemical vapor deposition (UHV-CVD). This multi-layer Si-O superlattice forms a new type of superlattice, semiconductor-atomic superlattice (SAS). According to the preliminary results, high-resolution cross-sectional transmission electron microscopy (HRTEM) shows epitaxial system. Also, the current-voltage (I-V) measurement results show the stable and good insulating behavior with high breakdown voltage. It is apparent that the system may form an epitaxially grown insulating layer as possible replacement of SOI, a scheme investigated as future generation of high efficient and high density CMOS on SOI. Since our scheme is epitaxial, three-dimensional integrated circuits (3D-ICs) may finally be realized in silicon-based technology. Therefore it is important to determine how good is the epitaxially grown silicon beyond a relatively thick Si-O superlattice. This work was supported by Grant(R05-2002-000-00565-0) from the Basic Research Program of the Korea Science & Engineering Foundation.

NS-TuP3 Synthesis of Nanocrystalline Semiconductors and Phosphors by Thermal Self Assembly, M. Abboudi, Universite Abdelmalek Essaadi, Morocco; S.Y. Seo, J. Bang, University of Florida; A. Benali, Universite Abdelmalek Essaadi, Morocco; P.H. Holloway, University of Florida

A new method has been used to produce luminescent and semiconducting nanopowders by thermo-decomposition of precursors prepared in situ by a direct solid state reaction. This represents a new self assembly approach for the synthesis of nanocrystalline materials. Oxide phosphors prepared by this method include ZnGa₂O₄ doped with europium or manganese, and Y₂O₃ doped with europium. All the synthesized powders have been characterized by X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). The photoluminescence and the cathodoluminescence from these phosphors with an average particle size of ≈ 50 nm have been studied with varying doping concentrations. Optimized concentrations will be reported and the luminescent spectra shown to be characteristics of the normal transitions for the dopants. The relative luminescence efficiencies will be shown to be good for these nanoparticles. We have also prepared nanocrystalline GaN powders, and will report on the defect structure with luminescence data. Finally, synthesis of Fe₂O₃ with particle diameters ≈ 25 nm, and Ce_{0.8}Gd_{0.2}O₃ with a specific surface area of 29 m²/g will be reported. Potential applications of these nanoparticles to phosphors, catalysts, photovoltaics, data storage, fuel cells and sensors will be discussed.

NS-TuP4 The Effects of Molybdenum-Oxide and Diamond on Field Emission, T. Tyler, D. Jaeger, A. Kvit, North Carolina State University; V. Zhirnov, Semiconductor Research Corporation; J. Hren, North Carolina State University

Refractory metals such as molybdenum and tungsten are frequently used in field emission applications, most often in the form of single tips or arrays of tips. Such field emitters have been studied in great detail over the past thirty years. The addition of an 'intentional' coating material (e.g. dielectric deposits such as aluminum-oxide or diamond) to improve emitter performance has been widely studied as well. However, there has been a lack of control of substrate effects (e.g. the presence and nature of oxides) in combination with coating effects. Carefully controlled morphological and compositional information is now required for a more complete analysis. We report here on combined studies of field emission, with high-resolution transmission electron microscopy (HRTEM), with computer simulations of local electric fields. Current versus voltage data is obtained during field emission, while HRTEM is used to determine morphology and composition (using electron energy loss spectroscopy). Computer simulations of

electrostatic effects, employing finite element methods, are then conducted using the morphologic and compositional information of the composite emitter structure, obtained from HRTEM. The magnitude and distribution of the surface potential barrier and the local field strength at the apex of the field emitter can thus be determined. The results also can provide information on the materials' electronic properties, such as the dielectric constant, trap density, and carrier velocity. The non-destructive nature of these experiments makes comparison studies possible; e.g. molybdenum needles, both oxidized and non-oxidized, are compared with needles coated with layers of nano-diamond.

NS-TuP5 Formation of Nanoporous Noble Metal Films by Electrochemical Dealloying of Pt_xSi_{1-x}, J.C. Thorp, K. Sieradzki, N. Dimitrov, S.T. Picraux, Arizona State University

Electrochemical dealloying of metallic alloy mixtures provides a novel way to form nanoporous structures. In the present study we demonstrate the extension of this concept to metal-silicon alloys on silicon platforms for Pt_xSi_{1-x}. The Pt_xSi_{1-x} (x = 50 and 25%) alloys are formed by deposition and thermal treatment. Thermal reaction of Pt films is used to form PtSi silicide layers and co-deposition for more silicon rich alloys. The films (200 to 800 nm thick) are then dealloyed in concentrated HF by an electrochemical process that leaches out the silicon. Anodic polarization curves are used to establish the optimum potential for dealloying, for example near +400 mV (SCE) for PtSi with current densities of approximately 10 mA/cm². Rutherford Backscattering Spectrometry (RBS) demonstrates the formation of a pure Pt layer on the metal silicide layer as dealloying process progresses and thus provides a direct observation of the dealloying kinetics. The resulting morphology of the nanoporous noble metal structures is determined by scanning electron microscopy. Results are presented for various Pt silicon alloys and dealloying conditions, and preliminary results will be discussed for Au silicon alloys. These nanoporous noble metal thin film structures provide high surface area electrodes on Si. Such nanostructures are of interest for microscale electrochemical sensing and microfuel cells.

NS-TuP8 Solvothermal Synthesis of Nanocrystalline γ -Fe₂O₃ in Toluene, C.-S. Kim, J.-H. Park, B.K. Moon, H.J. Seo, Pukyong National University, Korea; B.-C. Choi, Pukyong National University, Korea, South Korea

The synthesis of γ -Fe₂O₃ nanoparticles has been performed in solvothermal route. The nanocrystalline particles were obtained after synthesis using two different temperatures of 130°C and 180°C for 10 hrs in an autoclave, where iron pentacarbonyl is thermally decomposed in toluene solutions in the presence of trimethylamine N-oxide as an oxidant. X-ray diffraction and transmission electron microscopy shows that the product has uniform maghemite structure with average particle size below 30nm. The specific surface area of the γ -Fe₂O₃ nanocrystalline powder was investigated using BET surface area analyzer. Influence of synthesis conditions such as synthesis temperature and molar ratio of precursor to solution on the size and size distribution of the product was also discussed.

NS-TuP9 Nanopipes in Single Crystal Transition-metal Nitride Layers, D. Gall, Rensselaer Polytechnic Institute

Nanopipes are 1-nm-wide open pores that extend through the entire thickness of epitaxial NaCl-structure transition-metal nitride layers. They form due to a combination of anisotropic surface diffusion and atomic shadowing effects. Their shape, orientation, and arrangement can be controlled by ion-irradiation and deposition angles. CrN, TaN, ScN, and TiN layers were grown on MgO(001) at 600-1000 °C by ultra-high-vacuum magnetically-unbalanced magnetron sputter deposition in pure N₂ and N₂+Ar discharges at 3-20 mTorr. These deposition conditions result in a highly anisotropic surface diffusion with hop-rates that are 7 orders of magnitude smaller on (111) versus (001) surfaces. This anisotropy leads, during growth under limited adatom mobility conditions, to kinetic surface roughening and the development of deep surface cusps which cause atomic shadowing and the formation of nanopipes that are elongated along the [001] growth direction. The nanopipes have rectangular cross-sections and form self-organized arrays aligned in orthogonal [100] and [010] directions, precisely replicating the in-plane correlation of the surface morphology. Non-normal deposition increases the level of atomic shadowing and introduces a controlled tilt to the nanopipes. Increasing the N₂+Ar ion irradiation flux or decreasing the N₂ partial pressure (and, hence, the steady-state N coverage) during growth provides a corresponding increase in cation

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surface mobilities leading to smoother surfaces, less atomic shadowing, and partial or full suppression of nanopipe formation.

NS-TuP10 Nanopatterning of Hydrogen Silsesquioxane Resist, M.J. Word, I. Adesida, University of Illinois at Urbana-Champaign

Creating nano-scaled structures in semiconductor materials generally begins with the use of high-resolution lithography techniques and resists. Electron beam lithography is capable of creating isolated structures less than 10 nm in width when utilized with high-resolution resists such as hydrogen silsesquioxane (HSQ). In addition to these isolated structures, it is also important to characterize the resist when more complex and denser structures are required. In our study we characterized the resolution of HSQ resist in the form of densely packed gratings. We began by examining the surface of very thin films of HSQ resist down to a thicknesses of 100 Å in order to determine the limits for successful processing using lithography techniques. Using a JEOL JBX-6000FS electron beam lithography machine operating at 50 kV with a current of 20 pA, we then exposed samples of HSQ at various film thicknesses with gratings having periods as small as 20 nm. We use the results to characterize the resolution limits of HSQ with respect to film thickness, dosing, and grating periodicity. In addition, we discuss the transfer of nanometer-scale patterns into InP and other semiconductor materials with exposed HSQ gratings acting as the etch mask. H. Namatsu, *J. Vac. Sci. Technol. B* 19, 2709 (2001).

NS-TuP11 On the Study of Growth Behavior of Carbonaceous Tips by Electron Beam Induced Deposition using Preprocessing Methods, S.H. Kim, Korea Electronics Technology Institute, South Korea; *Y.J. Choi,* Korea Electronics Technology Institute, South Korea

For the investigation of high aspect ratio structures with SPM, the cantilevers with very sharp and long tips are useful. The carbon nanotube (CNT) tips and electron beam deposited (EBD) tips are effective candidates for the high aspect ratio tips. Although EBD tips are duller than CNT tips, they have an advantage of simple fabrication process over the CNT tips. EBD tips can be simply fabricated by aligning the electron beam directly down the vertical axis of Si cantilever and then irradiating a single spot on the cantilever for a proper time in the dominant atmosphere of residual gases generated by the oil of the diffusion pump of the Scanning Electron Microscope (SEM). The height and the base diameter of the EBD tips can be controlled by adjusting the control parameters of the SEM. However, the EBD tips cannot grow over 1 μm in the residual gas atmosphere. We could enhance the height of tips by dipping the cantilever into the organic solvents which contain aromatic or aliphatic hydrocarbon, drying it in the vacuum chamber and irradiating electron beam. With this process, we could acquire the tip whose base diameter is 0.18 μm and effective length is 3.18 μm. In addition, we observed that the growth behavior of the tips are different in accordance with the species of the chemicals and we will discuss the effects of the organic solvents on the growth of the tips. Albert Floch, Jordi Servat, *J. Vac. Sci. Technol. B*, Vol 14, No. 4 Jul/Aug (1996). M. Wendel, H. Lorenz, and J.P. Kotthaus, *Appl. Phys. Lett.* 67(25) (1995).

NS-TuP12 Probing Adhesion and Friction on Nanostructured Surfaces with Chemical Force Microscopy, C.L. Berrie, J.E. Headrick, University of Kansas

Chemical functionalization of AFM probe tips allows regions of different composition on the surface to be identified even in the absence of topographic variations. Unfortunately, many of the established chemical-functionalization methods lead to a significant increase in the size and curvature of the tip radius, which effectively sacrifices the resolving ability of the AFM measurement. In this work, we have chemically-modified commercially-microfabricated Si₃N₄ AFM tips with a variety of self-assembled alkylsilane monolayers having distinct terminal functionalities, such as -CH₃, -CH₂Br and -COOH, using a fabrication process that minimizes undesirable resolution-loss due to tip growth. We have measured the adhesion forces and friction loops between these functionalized tips and various substrates, including nanostructured substrates where the chemical composition of the surface varies on the nanometer length scale (for example from hydrophobic to hydrophilic). The nanostructured surfaces are created using the AFM. These results will help us to understand the resolution limits of these techniques by allowing the investigation of the sensitivity of the technique to pattern size.

NS-TuP14 In-situ Tip Preparation and Nanoscale Surface Modification using STM Manipulation, V. Iancu, A. Deshpande, S.-W. Hla, Ohio University

Single atom manipulation with a scanning tunneling microscope (STM) tip on crystal surfaces requires an extremely fine control over the tip-atom-surface junction. The shape of the STM-tip and the chemical elements that constitute the tip-apex are vital for a successful atom manipulation with atomic scale precisions. Here we report an in-situ tip preparation technique useful to fabricate stable STM-tips with a known chemical element at the tip-apex. The experiments are conducted at an ultra-high-vacuum conditions on a Ag(111) surface at 4.8 and 75 K sample temperatures. During the experiment, the STM-tip, made of polycrystalline tungsten wire, is gently dipped into the substrate and the tunneling voltage is increased to 3 V. The penetration depth is precisely controlled. The shape of the holes created by the tip dipping indicates that the tip becomes sharper by repeating the procedure. This is due to the local heating during the tip-sample mechanical contact that re-shapes the structure of the tip-apex. In addition, variation of the tip-height and tunneling voltage during the procedure results in different impact force. By applying suitable impact force with the STM-tip, atomic scale surface steps and Ag islands can be created locally. This entire procedure will be useful to conduct new nanoscale experiments or to test the strength of the material at an atomic level. S.-W. Hla, K.-F. Braun, K.-H. Rieder, "single atom manipulation mechanisms during a quantum coral construction", *Phys. Rev. B* rapid communication (2003) in press. L. Bartels, G. Meyer, K.-H. Rieder, "Inducing all steps of a chemical reaction with the scanning tunneling microscope tip: Towards single molecule engineering", *Phys. Rev. Lett.* 85 (2000) 2777-2780.

NS-TuP15 Tomographic Reconstruction of Doping Profile and Device Structure in Si MOSFET Devices with a sub 10 nm Spatial Resolution, R.K. Bansal, J.M. Fitz-Gerald, R. Hull, D.H. Anjum, University of Virginia

Due to a phenomenal reduction in the size of semiconductor devices over the last two decades there is a need to develop better characterization methods which can probe the devices in three dimensions with a high spatial resolution. The present work aims at tomographic reconstruction of the device structure and doping profile in semiconductor devices with sub-10 nm resolution. This involves using a Focused Ion Beam (FIB) to sputter away layers of atoms and subsequently image the cross-section of the device using a high resolution scanning electron microscope (SEM). This process is repeated, followed by concatenation of these images in the computer, to obtain a three dimensional reconstruction of the device. The SEM used for this work is the state-of-the-art JEOL 6700F field emission SEM which has a spatial resolution of 1 nm. Also under investigation is the possibility of observing the spatial dopant distribution in the device and the enhancement of the doping contrast by using hydrogen surface passivation. This study is currently being done on short channel length (50 nm - 1 μm) MOSFETs with strained and unstrained Si channel and can be extended to other devices and material systems.

NS-TuP16 Imaging of DNA Strands with the Low Energy Electron Point Source (LEEPS) Microscope, A. Eisele, Universität Marburg, Germany; *B. Völkel, M. Grunze,* Universität Heidelberg, Germany; *A. Götzhäuser,* Universität Marburg, Germany

A low energy electron point source (LEEPS) microscope is used to image freestanding DNA multistrands. These span 100 nm wide openings in a thin silicon sample holder. The holographic images are analyzed by assuming a mask model and vacuum wave propagation. We extract the correct source-to-object distance by the analysis of cuts through numerical reconstructions in the object region with an accuracy of 40 nm. Upon variation of the lateral and axial source position, the reconstructions show reproducible object structures and focus behavior. The smallest reproducibly resolved features have dimensions of 1 nm. Due to the low energy (40 eV) of the field emitted electrons, LEPS microscopes generate images with a much higher contrast than conventional electron microscopes.

NS-TuP18 Second Harmonic Piezoresponse Force Microscopy: A Probe of High Order Ferroelectric Processes, R. Shao, University of Pennsylvania; *S.V. Kalinin,* Oak Ridge National Laboratory; *D.A. Bonnell,* University of Pennsylvania

Piezoresponse Force Microscopy (PFM) has been widely accepted as an important technique for imaging ferroelectric domains. The principle of PFM is the detection of the electromechanical response to an ac voltage applied at a tip/surface contact. There are two unresolved issues associated with PFM. The first is the degree of perturbation to ferroelectric

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domain polarization imposed by the ac voltage. The second is a dilemma involving switching mechanisms during acquisition of the hysteresis loop. To address these issues, we have measured the second harmonic of the electromechanical response to the ac imaging voltage on various ferroelectric materials as a function of both frequency and amplitude of the voltage. A theoretical model has been established that relates the ferroelectric relaxation to the second harmonic response. The approach is extended to an imaging technique, Second Harmonic Piezoresponse Microscopy, that maps the distribution of relaxation times on surfaces by acquiring the spatial distribution of the second harmonic response.

NS-TuP19 Lithographic Patterning using Near-field Scanning Optical Microscopy, R.E. Hollingsworth, ITN Energy Systems, Inc; C. Veauvy, M. Treaster, J.D. Beach, R.T. Collins, Colorado School of Mines

We report the development of a near-field scanning optical microscope (NSOM) designed specifically for direct write lithography on 4" substrates. Direct write lithography is ideally suited to research use where rapid turn around, flexible pattern generation and much lower cost than production tools are very important. At present, electron beam lithography is the most commonly used direct write technique, although scanning probe microscopes are receiving increasing attention. The advantages of NSOM lithography over these other direct write approaches are the ability to use conventional optical photoresists and to combine near-field with far-field optical exposure. As an optical technique, NSOM also avoids concerns of high-energy electron damage and vacuum compatibility inherent to e-beam lithography. Our approach uses state of the art mechanical translation stages that take steps a fraction of the typical NSOM resolution. This allows patterning over typical wafer dimensions with none of the stitching errors inherent in other techniques. The microscope also functions in standard NSOM characterization modes allowing, for example, nanoscale topography and reflectance to be measured and used in feature characterization and pattern registration. In this presentation, we will discuss the microscope design, performance tests, and photoresist process development for 100nm scale features and for pattern transfer into substrates and films. Microscope use in example applications such as quantum point contacts, surface plasmon enhanced near-field optics, and nucleation sites for seeded film growth will be presented.

NS-TuP20 Electroless Metal Discharge Layers for Electron Beam Lithography, S.L. Brandow, M.-S. Chen, W.J. Dressick, R. Bass, Naval Research Laboratory; E. Dobisz, Hitachi Global Storage Technologies

Substrate charging during e-beam lithography on non-conductive materials can lead to severe problems in pattern placement accuracy and critical dimension (CD) error. Current methods of controlling charge include the use of conducting polymers or evaporated metal films as charge dissipation layers. We report an alternative approach utilizing ultrathin (i.e., 15-30 nm) Cu films deposited by electroless metal deposition. Our method involves the sequential chemisorption of an aminosiloxane film to the substrate of interest, binding of a colloidal Pd/Sn electroless catalyst, and brief immersion in an electroless Cu bath to deposit the ultrathin Cu film. This ligand based approach permits sufficient control of Cu thickness and uniformity to satisfy electrical conductivity, adhesion, and transparency constraints required for discharge layers. The deposition process is performed under ambient, aqueous conditions which are track-line compatible and thus should have cost advantages over conventional CVD based metallization processes. The grounded Cu film, deployed here as a resist underlayer, eliminates the 0.1 - 0.4 micron subfield stitching errors normally observed in the absence of the Cu film during resist patterning on a glass or insulating substrate. The Cu is readily removed using a nitric acid wet etch following patterning.

NS-TuP21 Metal Pattern Transfer from Microstructured Self-Assembled Monolayer Templates to Polymer Substrates by an Imprinting Method, S. Imura, N. Saito, H. Sugimura, O. Takai, Nagoya University, Japan

Nanoimprint lithography is expected to play a crucial role in device nanoprocessing. The method has been employed in order to transfer a minute structure on a mold to a polymer film. Besides fabrication of such 3D polymer nanostructures, nanopatterning a functional material other than polymers through nanoimprint is of further interest. Here we show the first demonstration of metal pattern formation by a imprinting method in which a metal micropattern deposited on a microstructured template was directly transferred onto a polymer substrate. First, a microtemplate was fabricated as follows. An organic self-assembled monolayer was formed from 1-undecanol on a Si substrate of which surface oxide was removed by HF etching. This monolayer was micropatterned by a photolithographic method. Due to irradiation at a

wavelength of 172 nm, the monolayer was photochemically decomposed and the underlying Si was oxidized. Consequently, a micropattern on a photomask was printed on the sample as a micropattern consisting of the unirradiated monolayer and photochemically formed SiO₂. Next, this microtemplate was immersed in a tin solution, a palladium solution and a Ni electroless plating solution, in that order. Ni was deposited selectively on the unirradiated monolayer while the oxide surface remained undeposited. Finally, this Ni micropattern deposited on the template was transferred onto a polymer substrate. The template was heated to a temperature of 180 °C and pressed into a polymethylmetacrylate (PMMA) substrate at a pressure of 10 MPa. The Ni micropattern was successfully transferred from the template to the PMMA substrate. @FootnoteText@ @footnote 1@H. Sugimura et al. Langmuir 16, 885 (2000).

NS-TuP22 Photolithographic Structures with Precise Controllable Nanometer-Scale Spacings Created by Molecular Rulers, M.E. Anderson, L.P. Tan, M. Mihok, H. Tanaka, M.W. Horn, P.S. Weiss, Pennsylvania State University

The combination of conventional lithographic techniques with chemical self-assembly allows for the creation of nanostructures whose spacing and edge resolution reach nanometer-scale precision. The controlled placement and thickness of self-assembled multilayers composed of alternating layers of α - and ω -mercaptoalkanoic acids and coordinated metal ions form precise "molecular ruler" resists to produce tailored, lithographically defined patterns. @footnote 1,2@ This resist is selectively deposited onto initial parent gold structures, metal is deposited, and the resist is lifted off, thereby leaving daughter structures whose spacing from the parent depends on the thickness of the resist. For future device fabrication with this technique, it would be advantageous to position these gaps selectively on the surface. We report here a method to accomplish this purpose by combining photolithography and molecular rulers. After forming the molecular resist, conventional photoresist is spin-cast onto the wafer and the photomask is aligned with the parent structure to place daughter structures only in selected locations. After exposure, development, metal deposition, and lift-off of both the photoresist and molecular resist, the final product is a wafer with daughter structures and gaps selectively oriented to create the desired hierarchical nanostructures. @FootnoteText@ @footnote 1@ A. Hatzor and P.S. Weiss, Science 291, 1019 (2001). @footnote 2@ M. E. Anderson, R. K. Smith, Z. J. Donhauser, A. Hatzor, P. A. Lewis, L. P. Tan, H. Tanaka, M. W. Horn, and P. S. Weiss, Journal of Vacuum Science and Technology B 20, 2739 (2002).

NS-TuP23 Formation and Characterization of Nanopores, T. Schenkel, V.R. Radmilovitch, A. Persaud, S.-J. Park, Lawrence Berkeley National Laboratory; J. Nilsson, Lawrence Livermore National Laboratory

The ability to form holes in membranes with diameters of only a few nanometers (1 to 10 nm) is of interest in many fields of nanometer scale science including single molecule studies, ion proximity lithography, and single atom doping. We report on studies of nanopore formation by local deposition of material in a dual beam focused ion beam system (FIB). Large holes with diameters of tens of nanometers are closed by the local deposition of platinum and TEOS oxide. We compare results from electron beam and ion beam assisted deposition of materials. Hole structure evolution is monitored in situ during hole closing by SEM. Hole profiles, local crystalline structure and materials composition are characterized ex situ by TEM. Nanopores with diameters in the 5 nm range have been formed in low stress silicon nitride membranes. We will discuss process reproducibility, and mechanisms of local structure evolution. @footnote 1@ @FootnoteText@ @footnote 1@ This work was performed at the National Center for Electron Microscopy at the E. O. Lawrence Berkeley National Laboratory and was supported by the National Security Agency and Advanced Research and Development Activity under Army Research Office contract number MOD707501, and by the U. S. Department of Energy under contract No. DE-AC03-76SF00098.

NS-TuP24 Probe-Scanned Traces with Chemical Reversibility on Organosilane Self-Assembled Monolayer Surfaces, N. Saito, S.L. Lee, H. Sugimura, O. Takai, Nagoya University, Japan

Amino-terminated self-assembled monolayers (SAMs) on silicon substrate have a potential as templates for biosensor or molecular devices. Since amino groups are able to link with target molecules such as deoxyribonucleic acid (DNA) and antibody-forming cell, many researchers had investigated amino-terminated SAMs. To fabricate components of future micro-devices, such templates must offer high chemical reactivity which is restricted to specific micro-regions. Thus, the amino-terminated

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regions must be prepared on given points of a substrate. Such a microstructure can be accomplished by maskless lithography techniques such as focused ion beam lithography and electron beam lithography. However, these lithography techniques cause a great deal of damage to the amino-terminated surface of a SAM due to the excessive energy applied. Considering this, we determined we had to develop a soft chemical lithography process for the reversible oxidation-reduction reaction of amino groups. Scanning probe lithography (SPL) is based on electrochemical theory and can be employed to realize such a soft process by controlling the applied potential. SPL had been applied in many cases, however, for the elimination of SAMs. In our present research, we have attempted, through chemical lithography, to produce amino-terminated regions on a sample surface without changing any other part of molecule. Amino-terminated SAM samples were prepared from p-aminophenyltrimethoxysilane through chemical vapor deposition. The amino-terminated surfaces were converted into nitroso-terminated surfaces at positive bias voltages. Moreover, the nitroso-terminated surfaces were reconverted into amino-terminated surfaces. The changes of functional groups on the surfaces were traced by Kelvin probe force Microscopy and atomic force microscopy.

NS-TuP25 Exploration of Chemical Bonding Forms for Producing Organic Monolayers Directly Attached to Silicon, N. Maeda, N. Saito, H. Sugimura, O. Takai, Nagoya University, Japan

Self-assembled monolayer (SAM) formed through the chemical reaction between 1-alkene and hydrogen-terminated silicon (Si-H) is an attractive material for molecular electronic devices, since such a monolayer is directly attached to Si without inserting an oxide layer. This is advantageous for electronic applications of the SAMs and is distinct from an organosilane SAM on Si which needs the oxide interlayer. Furthermore, such a directly-bonded SAM is chemically durable to HF solution more than the organosilane SAM.¹ However, an understanding of chemical reactivities of Si-H surfaces to organic molecules is still in an insufficient level. Here we report on SAM formation on Si-H from various precursor organic molecules including 1-hexadecan, phenylacetylene, 1-undecanol, 4-bromomethylbiphenyl, p-phenylenediamine, terephthalaldehyde, etc. Si-H samples were prepared through the etching of Si(111) substrates in 5%-HF. A Si-H sample was then refluxed at a temperature ranging from 100 to 180 °C for several hours in a precursor liquid or a organic solution of a precursor under an atmosphere purged with N₂.² The treated sample was examined with a water contact angle measurement, X-ray photoelectron spectroscopy (XPS) and infrared spectroscopy in order to confirm SAM formation. In the case of 1-hexadecan, phenylacetylene, 1-undecanol, there were no oxidized Si peaks in XPS. This indicates that densely packed monolayers were formed so that the Si substrates were protected from oxidation. However, in the case of the other precursors, the Si substrates oxidized showing that such monolayers were less densely packed.¹ ² N. Saito, S. Youda, K. Hayashi, H. Sugimura and O. Takai, Chem. Lett. 31, 1194 (2002).

NS-TuP26 Fabrication of Cylindrical Cu Nanorods on an Indium-Tin-Oxide Substrate, S. Asakura, K. Oda, Waseda University, Japan; **A. Hozumi,** National Institute of Advanced Industrial Science and Technology, Japan; **A. Fuwa,** Waseda University, Japan

Increasing attention has recently been paid to the fabrication of copper (Cu) arrays of nm-scale in order to realize an ultrahigh-density electron emission source. Among the several methods, the use of diblock copolymer (BC) thin film is promising, since an ordered nanoporous structure can be easily obtained from the copolymer thin film by chemical treatment. Here we report the fabrication of cylindrical Cu nanostructures onto an indium-tin-oxide (ITO) substrate through an electrodeposition using a BC thin film as a template. First, a mixture of polystyrene (PS, 70 wt.%) / polybutadiene (PB, 30 wt.%) BCs and dehydrated toluene was stirred for 2 h at room temperature. Next, the solution was spin-coated on the ITO surface and dried in air for 24 h at a temperature of 140 °C. Due to this treatment, the PB component formed cylindrical domains in a matrix of the PS component as confirmed by an optical microscope. Subsequently, the sample was photoirradiated with vacuum ultraviolet (VUV) light of 172 nm in wavelength for 30 min at 10³ Pa. As a control experiment, identical BC thin film/ITO sample was sonicated in dehydrated toluene for 30 min. Finally, each sample was treated in an electroplating solution to deposit Cu on it. Using a scanning electron microscope, we confirmed that the Cu deposition selectively occurred inside the cylindrical nanopores where the PB domains were photochemically eliminated. The cylindrically shaped Cu nanorods on the ITO surface were less than 800 nm in diameter and several hundreds nm in length. Our result presented here

demonstrated that the PB domains were removed completely due to VUV irradiation and the PS matrix served as a mask to prevent Cu deposition. On the other hand, in the case of the chemical treatment, no Cu deposition was observed. This indicates that the PB domains still remained on the ITO surface. Our VUV treatment was found to be effective for preparing the nanoporous structures in the BC thin film.

NS-TuP27 Organic Self-Assembled Monolayers Covalently Linked to Diamond Electrode Surfaces, R. Ohta, N. Saito, Y. Inoue, H. Sugimura, O. Takai, Nagoya University, Japan

Diamond has excellent properties as an electrode material for electrochemical sensors, besides its well-known properties as the hardest material in nature. It has a wide potential window and chemical stabilities in various environments. Chemical functionalization of diamond surfaces is a powerful means in order to provide chemical selectivity and sensitivity to the diamond surfaces. Thus, it is a crucial technique for developing diamond-based chemical sensors. However, in actual applications of a modified diamond electrode, its surface is needed to be durable chemically and mechanically. Organic molecular monolayers covalently linked to diamond surfaces meet these demands and promising candidates. In this research, we have studied both vapor phase and liquid phase processes for the modification of hydrogen-terminated diamond to several organic molecules such as 1-undecanol and 1-hexadecan as well as that of hydroxyl-terminated diamond to organosilane molecules such as alkylsilane and aminosilane. The molecules were fixed onto the diamond surfaces through covalent bonds such as C-O-C, C-C and C-O-Si and consequently formed self-assembled monolayers. The monolayers were characterized by scanning probe microscopy, X-ray photoelectron spectroscopy and infrared spectroscopy. These results will be discussed with the electrochemical behavior of the modified-diamond surfaces. Micropatterning of the diamond surfaces will be also presented.

NS-TuP28 Photochemical Reaction of Organosilane Self-Assembled Monolayers as Studied by Scanning Probe Microscopy, H. Sugimura, N. Saito, I. Ikeda, Y. Ishida, K. Hayashi, O. Takai, Nagoya University, Japan

Photopatterning of organosilane self-assembled monolayers has attracted attention due to a wide variety of applications of micropatterned monolayers as micro templates for immobilizing biomolecules, nanoparticles, polymers and so forth. For such advanced applications of the micropatterned monolayers, the study on photochemical reactions proceeding on the monolayers due to photo irradiation is indispensable. In this study, we used two types of the monolayers prepared on Si substrates from octadecyltrimethoxysilane (ODS) and chloromethylphenyltrimethoxysilane (CMPHS). Each monolayer was micropatterned by irradiating the monolayer through a photomask with a light at 172 or 244 nm in wavelength in the presence of atmospheric oxygen molecules. Although, the CMPHS monolayer could be micropatterned by both the light at 172 and 244 nm, patterning of the ODS monolayer was capable only by the light at 172 nm. Generation of activated oxygen atoms through the excitation of the atmospheric oxygen molecules had a crucial role in photopatterning at 172 nm, while excitation of aromatic rings was the key process for patterning of the CMPHS monolayer at 244 nm. Photochemical reactions proceeded on the monolayers were further studied in minute scale through changes in friction and surface potential due to photo-irradiation by means of scanning probe microscopy, that is, lateral force microscopy and Kelvin-probe force microscopy, respectively. These results will be discussed with results obtained from spectroscopic studies such as X-ray photoelectron and infrared absorption spectroscopies.

NS-TuP29 Self-organizing Processes in Connection with Nanocluster States, W. Schommers, M. Rieth, Forschungszentrum Karlsruhe, Germany; **S. Baskoutas,** University of Patras, Greece

In the past experimental as well as theoretical investigations have shown that the structure of metallic nanoclusters most often deviates significantly from those of the bulk. With the help of molecular dynamics calculations we demonstrate how the transition from bulk structured materials to nanostructured clusters might take place, e.g., during a production process. In connection with such structural transitions one result is rather interesting: the occurrence of meta-stable cluster states. The conditions under which such meta-stable nanostructures might be possible and how their life-time could be influenced is systematically investigated. Such structurally meta-stable atomic compounds are commonly known in connection with huge complicated inorganic molecules. Especially in biology such meta-stable molecules are most often observed to store energy or to act as propulsion system in one way or another by changing

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parts of its structure. Our molecular dynamical investigations have shown that specific metallic nanoclusters behave similar. In this connection we also tried to answer the following questions: How is the dynamics of nanoclusters changed when they transform from the metastable to the stable state? Is this behavior restricted to specific materials? And what is the underlying mechanism?

Nanometer Structures

Room 308 - Session NS-WeM

Nanomechanics

Moderator: N.A. Burnham, Worcester Polytechnic Institute

8:20am **NS-WeM1 Dissipation in Few Atom Systems, J. Pethica**, University of Oxford, UK **INVITED**

9:00am **NS-WeM3 Quantitative Imaging of Local Electromechanical Properties of Ferroelectric Surfaces by Piezoresponse Force Microscopy, S.V. Kalinin**, Oak Ridge National Laboratory; **J. Shin**, University of Tennessee; **A.P. Baddorf, J.F. Wendelken**, Oak Ridge National Laboratory; **M. Kachanov, E. Karapetian**, Tufts University

Piezoresponse Force Microscopy has become the primary tool for the characterization of ferroelectric materials at nanoscale dimensions. Application of a periodic bias to the AFM tip in contact with the surface results in surface oscillations due to an inverse piezoelectric effect. These are detected with a lock-in amplifier to produce PFM amplitude and phase images. Special attention has been attracted to the potential of this technique for local spectroscopic measurements, i.e. the local electromechanical hysteresis loop of the material. Application of a dc bias or force to the tip can switch the local polarization, opening possibilities of PFM as a nanolithographic tool. Despite extensive effort, a detailed understanding of PFM imaging, including tip induced mechanical and electrostatic phenomena inside the ferroelectric, has not previously been achieved. Here, the analytical solution of the coupled electromechanical problem for piezoelectric indentation is used to derive the electric field and strain distribution inside the ferroelectric material, providing a complete continuum mechanical description of the PFM imaging mechanism. These solutions are used to quantitatively interpret PFM spectroscopic measurements and bias- and stress-induced domain behavior. It is shown that the dielectric gap formation at the tip surface junction due to surface contamination significantly affects the PFM imaging mechanism. Preliminary results of PFM imaging under controlled atmosphere and UHV conditions are presented.

9:20am **NS-WeM4 Evaluating Nanocomposite Strength at Individual Nanotube-Polymer Interfaces, S.R. Cohen, A.H. Barber, C.A. Cooper, H.D. Wagner**, Weizmann Institute of Science, Israel

Nanocomposites formed from carbon nanotubes have been proposed as an ultra-high strength material. Although bulk measurements of the properties of such nanocomposites support these claims, until this work the only direct microscopic investigation of the nanotube/polymer interfacial strength has been by theoretical predictions. We have developed two novel SPM-based techniques which measure, for the first time, the direct pull-out forces of individual nanotubes in a polymer matrix. In one approach, the nanotubes are mixed into an epoxy resin using a procedure which results in a porous structure with nanotubes bridging the pores and embedded into the polymer matrix. The SPM tip is used to drag these nanotubes out of a film formed by microtoming this structure. The force exerted is extracted from the SPM measurement, whereas embedded length is measured with the aid of TEM. In the second approach, a nanotube attached to an SPM probe is pushed into a polymer melt, and pulled out from the hardened polymer after cooling. Here, the SPM measurement is used to evaluate both the forces and embedded length. Our results verify the predicted high nanotube-polymer interfacial strength, and reveal trends correlated to fiber diameter and embedded length. (a) Carole A. Cooper, Sidney R. Cohen, Asa H. Barber, and H. Daniel Wagner Appl. Phys. Lett. 81, 3873-75 (2002); (b) Asa H. Barber, Sidney R. Cohen, and H. Daniel Wagner Appl. Phys. Lett. (June, 2003).

9:40am **NS-WeM5 Mechanics at the Nanoscale, T. Uchihashi, M. Higgins**, Trinity College, Ireland; **J.E. Sader**, E.T.S. Walton Visitor, Trinity College, Ireland, Australia; **S.P. Jarvis**, Trinity College, Ireland **INVITED**

Atomic force microscopy (AFM) evolved from the observation of the effects of mechanical contact in the scanning tunnelling microscope. Thus, even from its first inception, nanomechanics and atomic force microscopy have been inextricably linked. Whilst not all mechanical phenomena have been intentional or welcomed in AFM measurements there has also been a concerted effort to apply AFM to the investigation of mechanics at the nanoscale. Due to its highly localised measurement ability, the microscope

can be applied to characterise the mechanical response of materials too laterally specific to be investigated by Surface Forces Apparatus or nano-indentation devices. For example, measuring mechanical responses with a probe of lateral dimensions comparable to that of a single molecule provides an invaluable insight into the processes controlling if and how a molecule approaches another molecule or a membrane and how mechanical property variations in any intervening fluid can modify that interaction. We introduce a significantly modified AFM which includes the ability to control the force sensor directly via a magnetic field in order to make sensitive dynamic measurements and direct stiffness measurements. In addition, to isolate the measured interaction to the tip apex we have used a multiwalled carbon nanotube attached to the tip. For the extension of the method to include lateral activation, and hence open up the possibility of measuring local viscosity, a new shape of cantilever has been used. To understand the mechanics of our new force sensors we have employed finite element analysis (FEA) to assess and improve the design and for calibration.

10:20am **NS-WeM7 Nanomechanics of Cytoskeletal Proteins, J.G. Forbes**, NIAMS, NIH, DHHS; **K. Wang**, LMB, NIAMS, NIH, DHHS

Striated muscle is the primary source of biomechanical force in organisms from worms to man, and can be thought of as a composite material that is organized on several length scales. The motor protein in all muscles is myosin, which generates piconewtons force through its interaction with actin and the hydrolysis of ATP. The tiny force generated by a single myosin is amplified by aggregating large numbers of myosin heads into an ordered structure called the thick filaments. The thick and thin filaments are then assembled into the basic contractile machinery called the sarcomere that link serially from one end of the muscle cell to the other. Striated muscle shortens by the sliding of actin filaments as they are dragged towards the center of the myosin filaments. When muscle relaxes, its original length is restored elastically. An array of cytoskeletal proteins are required to regulate the size, assembly and function of the sarcomere, as well as transmit force and provide elasticity for restoring the structure. One such protein is the giant protein titin (3-4E6 g/mol), which spans half of the muscle sarcomere length. The passive elasticity of muscle at a physiological range of stretch arises primarily from the extension of titin. Nebulin serves as a ruler for the actin filaments and may alter their compliance and tensile strength. Other proteins such as dystrophin help transmit force out of the muscle and desmin forms intermediate filaments, which help to stabilize the sarcomere organization. We have studied the elastic properties of these motor and cytoskeletal proteins via force spectroscopy with the AFM. We have found that the elasticity of proteins can arise from mechanisms other than simple entropic elasticity. These mechanisms work at the nanoscale and may allow for their properties to be fine tuned to fit the need of muscle to work under a variety of conditions. These insights from biology may allow for the engineering of more effective elastic materials.

10:40am **NS-WeM8 Effect of the Ionic Strength on a Natural Lipid Bilayer Assembling and Stability: A Force Spectroscopy(nanomechanical) Study, S. Garcia-Manyes, M.J. Kogan, F. Sanz**, University of Barcelona, Spain; **D. Ludevid**, CSIC, Spain; **E. Giral**, University of Barcelona, Spain

Lipid bilayers have been widely studied on account of their biological interest regarding cell characterization, membrane protein transport, etc. In the last recent years many studies have been focused on the study of such membranes using Atomic Force Microscopy, since it gives chemical and topographic information in the nanometer scale. Some of these studies dealt with lipid deposition on flat substrates such as mica, silica or graphite either in the form of Langmuir-Blodgett films or after bilayer self-assembly. Some of these lipid surfaces have been used to support proteins in order to study lipid-protein interaction or to test new drugs. Most of these studies used synthesized bilayers for the a priori sake of reproducibility and simplicity in their chemical composition. In these work we present novel results concerning the study of a natural plant bilayer membrane formation under physiological conditions. By using force spectroscopy we demonstrate that solution ionic strength is crucial in the self-assembling process and that small variations in ionic strength give rise to huge variations in bilayer compactness. There is a threshold ionic strength under which bilayers are not self-assembled, connected with the charge repulsion between the hydrophilic charged heads of the molecule. As the ionic strength is increased the charge repulsion seems screened out and the assembling process achieved, and this is reflected in a discrete jump in the force plot. The force at which this break takes place (the so-called yield point) is highly influenced by the own magnitude of the ionic strength, and ranges from ~ 1.5 nN at 10 mM to ~ 9 nN at 1 M. A nanomechanical study concerning the elasticity of the bilayer, as well as an

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evaluation of the forces that take place (double layer, hydration forces, Van der Waals, etc.) is also included.

Organic Films and Devices

Room 318/319 - Session OF+NS-WeM

Molecular Electronics

Moderator: D. Cahen, Weizmann Institute of Science, Israel

8:20am **OF+NS-WeM1 Electronics and Mechanics with Single Molecules, P.L. McEuen**, Cornell University **INVITED**

It is now possible to make electronic and mechanical devices where an individual molecule is the active element. Examples include devices made from single-walled carbon nanotubes or single organic molecules. These molecular devices are proving to be wonderful systems for the study of the physics of materials at the nanometer scale. In this talk, I will review recent progress within our group on the electrical, electromechanical, and electrochemical properties of individual nanotubes and single molecules, as inferred from both transport and scanned probe measurements.

9:00am **OF+NS-WeM3 Understanding Charge Transport in Molecular Electronics, J.G. Kushmerick, R. Shashidhar**, Naval Research Laboratory

We use an experimentally simple crossed-wire tunnel junction to interrogate how factors such as metal-molecule coupling, molecular structure and the choice of metal electrode influence the current-voltage characteristics of a molecular junction. Results on junctions with symmetric and asymmetric metal-molecule contacts demonstrate that a specific molecular core can act either as a molecular wire or a molecular rectifier depending on its coupling to the metal electrodes. By tuning the coupling at the two metal-molecule interfaces through the use of different attachment chemistries and metal electrodes we are able to control the extent of current rectification. Experimental measurements and theoretical calculations demonstrate that the conductance of a molecular wire can be directly related to how well its π -conjugated backbone mimics an ideal one-dimensional metal. Finally, we will show that the conductance of a molecular junction scales with the number of molecules contacted, and that the π -systems of molecular wires connected in parallel are not strongly coupled. Initial results demonstrating the utility of in situ vibrational spectroscopy to characterize the molecular junction will also be presented.

9:20am **OF+NS-WeM4 Observation of Negative Differential Resistance Measured through Individual Molecules on Silicon at Room Temperature, N.P. Guisinger, R. Basu, A.S. Baluch, M.C. Hersam**, Northwestern University

In recent years, substantial progress has been made in the emerging field of molecular electronics. In particular, metal-molecule-metal junctions have been widely studied. In this paper, charge transport through molecule-semiconductor junctions is considered. The presence of the energy band gap in semiconductors provides opportunities for resonant tunneling through individual molecules, leading to interesting effects such as negative differential resistance (NDR). The ultra-high vacuum (UHV) scanning tunneling microscope (STM) allows individual molecules to be imaged, addressed, and manipulated on semiconducting surfaces with atomic resolution at room temperature. This paper considers two distinct chemistries on the Si(100) surface. Styrene reacts with Si(100) via a covalent silicon-carbon bond. On degenerately n-type Si(100), STM current-voltage characteristics on individual styrene molecules show clear NDR at negative sample biases of approximately -2.5 V and -4 V. However, at positive sample bias, the styrene is liberated from the surface via inelastic electron stimulated desorption (ESD). In an effort to minimize perturbation via ESD, individual 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO) molecules were bound to degenerately n-type Si(100). The exceptional stability of the silicon-oxygen bond allows charge transport measurements on TEMPO at high biases up to ± 5 volts without ESD. Similar to styrene, NDR is clearly observable at negative sample biases of approximately -3 V, -4 V, and -4.5 V. These effects will be explained by considering the energy band diagram of the semiconductor-molecule junction.

9:40am **OF+NS-WeM5 Molecular Materials and Devices, C.R. Kagan, A. Afzali, R. Martel, P.M. Solomon, L.M. Gignac, A.G. Schrott, B. Ek, C. Lin**, IBM T.J. Watson Research Center **INVITED**

Efforts to fabricate devices based on active molecular components have been driven by both the fundamental interest in using chemistry to build function at the molecular level and the looming technological expectation of the end of Moore's law. In this talk, we describe the directed assembly

of organic and metal-metal bonded supramolecular systems that are interesting materials for potential electronic and memory device applications. Molecules are chosen with head groups that bind to metal or oxide surfaces and tail groups that bind to metal electrodes or that template the growth of the particular molecular system. Optical spectroscopy, atomic force and scanning tunneling microscopy, electrochemistry, and electrical measurements are used to characterize the chemistry and physics of molecular assemblies and the behavior of devices. Self-assembled organic monolayers are used to fabricate reported field-effect transistor structures and to elucidate the important requirements necessary to successfully design two- and three-terminal molecular devices. We demonstrate the layer-by-layer assembly of metal-metal bonded supramolecules and utilize this approach to fabricate molecular devices.

10:20am **OF+NS-WeM7 Mediating Electronic Switching of Single Molecules Using Chemical Interactions, P.A. Lewis**, The Pennsylvania State University; *C.E. Inman*, University of Oregon; *J.M. Tour*, Rice University; *J.E. Hutchison*, University of Oregon; *P.S. Weiss*, The Pennsylvania State University

We have studied conjugated phenylene-ethynylene oligomers inserted into amide-containing alkanethiolate self-assembled monolayers using scanning tunneling microscopy in order to determine their physical and electronic properties when surrounded by a hydrogen-bonded matrix. The phenylene-ethynylene oligomers show stability in two conductance states, an ON and an OFF state. We observe fewer switching events between the ON and OFF states than previously reported for n-alkanethiolate matrices and attribute this to the rigidity due to the hydrogen bonds of the amide groups in the matrix. Furthermore, we demonstrate bias-dependent switching as a result of hydrogen bonding between the substituents of the inserted oligophenylene-ethynylene and the matrix molecules. We demonstrate that the chemical and physical environment of proposed molecular devices is crucial to their function and can be exploited to impart tunable electronic properties.

10:40am **OF+NS-WeM8 Two-Photon Photoemission Studies of Molecular Affinity Levels in Oligo-Phenylene Ethynylene Self-Assembled Monolayers, C. Zangmeister, S.W. Robey, R.D. van Zee**, National Institute of Standards and Technology

Two-photon photoemission has been used to study unoccupied electronic levels for a family of thiolated oligomeric phenylene-ethynylene self-assembled monolayers. Self-assembled monolayers of a three phenyl ring oligomer (OPE) and the same oligomer with a nitro group substituted for one hydrogen on the center ring (NO@sub2@-OPE) were formed on polycrystalline Au/Si substrates as well as [111] oriented Au on mica. This class of compounds has received attention because of measured conduction characteristics and the reported negative-differential resistance behavior of these compounds in nanometer-sized pore structures. Single-color, two photon photoelectron spectroscopy measurements were performed in the ultraviolet using frequency-doubled, subpicosecond pulses from a Ti:Sapphire-pumped optical parametric amplifier. For the OPE monolayers we have, based on the excitation energy dependence, identified an unoccupied level ca. 1 eV above the vacuum level. Using previous two-photon photoemission and inverse photoemission of condensed benzene layers as a guide we tentatively identify this as the remnant of the $e_{\text{sub}2\text{u}}$ unoccupied level for benzene localized on the carbon atoms of the phenyl ring. Results of studies on NO@sub2@-OPE layers will also be discussed.

Nanometer Structures

Room 308 - Session NS-WeA

Nanotribology

Moderator: R.W. Carpick, University of Wisconsin - Madison

2:00pm NS-WeA1 MEMS Tribological Coatings and Wear Debris Analysis, S.A. Smallwood, Air Force Research Laboratory; **K.C. Eapen**, University of Dayton Research Institute; **J.S. Zabinski**, Air Force Research Laboratory
Among the most significant challenges to developing reliable MEMS that have mechanical components are stiction, friction, and wear. One potential solution to this problem is to protect the devices with coatings, such as monolayers and hard self-lubricating materials. An essential aspect to developing these materials is to understand how surface chemistry, surface forces, wear, and MEMS performance are interrelated. Due to the small size and complex structure of MEMS, it is difficult to develop a fundamental understanding of these phenomena. Wear debris often has dimensions of < 1 mm and it may be hidden under the MEMS structures. In addition, few surface analytical techniques are available to precisely determine tribochemistry and wear mechanisms on MEMS structures. To combat tribological problems, perfluorinated ethers, esters, and mono- and di-alcohols were deposited on MEMS and their chemical/physical properties were studied and related to MEMS performance. AES, microRaman spectroscopy, and IR spectroscopy were used to probe surface chemistry. SPM and surface force measurement systems were used to understand forces at the MEMS scale. A technique to adequately coat complex MEMS structures will be discussed along with the mechanisms responsible for increasing MEMS electrostatic output motor lifetimes by up to three orders of magnitude.

2:20pm NS-WeA2 Nanotribological Properties of Ultrananocrystalline Diamond, D.S. Grierson, A.V. Sumant, University of Wisconsin-Madison; **J.E. Gerbi**, **J.A. Carlisle**, **O. Auciello**, Argonne National Laboratory; **R.W. Carpick**, University of Wisconsin-Madison

There is an increasing demand for materials applicable to rolling and sliding contacts in MEMS technology. Ultrananocrystalline diamond (UNCD) films have unique mechanical and tribological properties that exhibit great potential for increasing the reliability of micro and nanoscale devices. Fabrication of MEMS components with UNCD has already been successfully demonstrated, but a detailed understanding of the nanotribological behavior of UNCD surfaces has not yet been established. This study is aimed at probing both the top "as-grown" surface and the back surface (exposed by etching the substrate) of UNCD films. We will explore the effects of hydrogen termination on both surfaces by examining the morphological, adhesive, and frictional properties of the H-terminated vs. untreated UNCD films as a function of load, sliding speed, and relative humidity. Atomic force microscopy is used to examine the nanotribological properties of these surfaces, and XPS, AES, and SEM are used to characterize the surface structure and chemistry. We will discuss the relationships between nanotribological behavior, surface morphology, and surface chemistry of UNCD. These studies could also be of interest for biosensing applications involving H-terminated diamond surfaces.

2:40pm NS-WeA3 Effect of Electric Fields on Nanoscale Friction Properties of Self-assembled Monolayers: Towards Active Friction Control of Interfaces, S. Sundararajan, K.K. Kanaga Subramanian, P. Hattan, Iowa State University

The ability to actively control friction properties of an interface is of great interest to both nanotechnology and macroscale applications. We present our investigations on the effect of an external electric field on the micro/nanotribological properties of selected self-assembled monolayers (SAMs) using scanning probe microscopy (SPM). It is theorized that an external field would affect the structure of the SAMs, thereby affecting their tribological behavior. The SAMs studied include -CH₂(OH)-, -COOH and oligo (ethylene glycol) terminated alkanethiols, and amino terminated silane on Au/Mica due to their well known structures and tribological properties. Micro/nanoscale friction and adhesive forces between the SAMs and a Si@sub3@N@sub4@ tip are studied as a function of applied external AC and DC fields to identify switchable friction states of the SAMs. This study would provide a better understanding of lubrication mechanisms at the molecular level and direct us to realize surfaces for active friction control.

3:00pm NS-WeA4 Impact of Atomic Corrugation on Sliding Friction as Probed by QCM, T. Coffey, North Carolina State University; **S.M. Winder**, University of South Carolina; **J. Krim**, North Carolina State University

At the atomic scale, friction is believed to originate primarily via sliding induced excitation of phonons. Theoretical predictions of the magnitude of phononic dissipation have been related to the atomic corrugation of the adsorbate/substrate potential. Using the Quartz Crystal Microbalance (QCM), we have measured the sliding friction of xenon adsorbed at 77 K onto three different surfaces. From lowest to highest atomic corrugation of the adsorbate/substrate potential, the surfaces are: Ag(111), Cu(111), and Ni(111). The QCM probe of sliding friction is the slifetime, which measures the slippage of the adsorbate atop the oscillating surface of the QCM. For monolayer coverages, we observed the following slifetimes: 2 ns for Xe/Ag(111), 1 ns for Xe/Cu(111), and 0.5 ns for Xe/Ni(111). We compare our slifetime results to published values of the atomic corrugation for these systems. We also discuss theoretical predictions for the impact of atomic corrugation on sliding friction. Fundamentals of Friction; Macroscopic and Microscopic Processes, ed. I.L. Singer and H.M. Pollock, Kluwer, Dordrecht (1992). M. Cieplak, E.D. Smith, and M.O. Robbins, Science 265, 1209 (1994). J. Krim and A. Widom, Phys. Rev. B 38, 12184 (1986).

3:20pm NS-WeA5 Wear Structures on the Nanometer Scale, R. Bennewitz, E. Gnecco, A. Socoliuc, E. Meyer, University of Basel, Switzerland

Friction force microscopy has been used to study the onset of wear. Abrasive wear could be detected down to single atomic layers at surfaces of ionic crystals. The wear debris was found to perfectly recrystallize in registry with the underlying surface. Furthermore, we have found a characteristic formation of nanometer-scale ripples perpendicular to the direction of scratching. These ripples are built in an interplay between strain-induced erosion, transport by the action of the tip, and diffusion. In a second part, we will present recent results of atomic friction experiments. The relation between atomic stick-slip instabilities and energy dissipation will be discussed based on experiments which exhibit very little dissipation.

3:40pm NS-WeA6 Tribological Investigation of AlNiCo Decagonal Quasicrystals by UHV AFM/STM, J.Y. Park, D.F. Ogletree, M. Salmeron, Lawrence Berkeley National Laboratory; **C.J. Jenks**, **P.A. Thiel**, Iowa State University

Tribological properties of the 10-fold and 2-fold surfaces of AlNiCo decagonal quasicrystals have been investigated in ultra-high vacuum using an atomic force microscope with WC-coated conducting tips. Using stiff cantilevers either tunnel current (STM mode) or force (AFM mode) can be used for feedback. The quasicrystal surfaces were cleaned by sputtering and annealing in UHV and characterized with low energy electron diffraction (LEED) and Auger electron spectroscopy (AES). Adhesion and friction of decagonal quasicrystal surface were measured by using contact mode AFM. From force-distance measurements we found that tip-sample adhesion on the clean 2-fold surface is two orders of magnitude higher than that of the air-oxidized surface. Because of this high adhesion, STM contrast was used to image surface morphology. The effects of in situ oxidation and carbon passivation on quasicrystal friction and adhesion will also be discussed.

4:00pm NS-WeA7 The One-Two Punch: Combining Chemical and Mechanical Stimuli at the Nanometer Size Scale, J.T. Dickinson, Washington State University

Bond breaking at surfaces due to stimuli such as exposure of materials to electrons, ions, photons, mechanical stress, or chemical agents are well established. We discuss in general the role of multiple stimuli (the "one-two punch") in the degradation and modification of materials and solid surfaces. We then show the nanometer scale consequences of combining localized mechanical stress (due to sliding contact with a scanning force microscope-SFM tip) and exposure to aqueous solutions. These nanotribological methods offer a top-down approach to controlled surface modification. Emphasis will be on results concerning tip induced material removal, recrystallization (at small normal forces), and unique patterning produced by scanning in super-saturated aqueous solutions. We also present results on the influence of an SFM tip in contact with polymers immersed in organic solvents. We show a new method for introducing very small amounts of highly localized patches of chemicals into a polymer surface. Finally, we show new evidence of a "1-2-3 punch", where we introduce radiation as a third stimulus on inorganic crystalline surfaces. The results shown have possible applications in sensors, nanofluidics, and

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optoelectronics. Models will be presented to explain the observed nanometer scale surface modifications.

4:40pm **NS-WeA9 The Wear of NaCl in Humid and Anhydrous Environments**, *P.E. Sheehan, L.J. Whitman*, Naval Research Laboratory

A recent report on the mechanism of dip pen nanolithography (DPN) indicated that wear on NaCl reveals the presence of a residual meniscus even under dry nitrogen. We have studied the wear of a NaCl single crystal by an AFM tip as a function of environmental humidity. In an anhydrous nitrogen environment, we find that the wear mechanism was not meniscus-based but rather mechanical, with the wear rate well-described by a thermal-activation model. By examining the wear track while varying both the temperature and the load, the activation volume and the activation energy could be measured. Introducing a slight amount of water into the anhydrous system dramatically changed the wear mechanism. In this case, salt dissolution and reformation occur, creating islands that are several atomic layers thick with clearly-observable step edges. Interestingly, the morphology of the islands indicates that they are fluid while in contact with the AFM tip and presumably its water meniscus; however, when the AFM tip is quickly removed, the islands solidify and can be imaged by a rapidly moving tip. This observation may lead to a method of patterning NaCl on the nanometer-scale. @FootnoteText@@footnote 1@ Rozhok, S.; Piner, R.; Mirkin, C. A.; J. Phys. Chem. B. (2003) 107 751-757.

5:00pm **NS-WeA10 Nanotribology - Tribochemical Wear of Muscovite Mica in Aqueous Solution**, *J.M. Helt*, The City University of New York College of Staten Island and the Graduate Center; *J.D. Batteas*, National Institute of Standards and Technology

Part I: Atomic force microscopy (AFM) is used to probe defect nucleation, prior to gross wear, of muscovite mica under aqueous environments. Nucleation is found to present itself initially as surface charging due to stress-induced tribochemical scission of the terminating surface bonds. As the surface bonds are continually cleaved, an ensemble of defects contribute to the $\sim 5.2 \text{ \AA}$ to $\sim 3 \text{ \AA}$ crystal lattice reconstruction observed in AFM topography and frictional force micrographs. Following lattice restructuring, abstraction of mica surface materials ensues, yielding visible wear scars ranging from $\sim 2 - 10 \text{ \AA}$ in depth. Environmental [OH⁻] profoundly affects the efficacy of wear events, which is illustrated by the acceleration or inhibition of wear with adjustment of pH under identical load and scan conditions. Part II: In AFM wear trials the area scanned is defined by the length of the slow (L_{sscan}) and fast scan axis. The ratio of L_{sscan} to image resolution (res , lines/image) defines the magnitude of the line step ($LS = L_{\text{sscan}}/\text{res}$). A contact radius - LS relationship indicates that overlap of successive scans will result if the contact radius - line step ratio (CRLS) is $< 1/2$. Consequently, the history associated with a single image scan is not equivalent at various loads due to the contact radius being proportional to the load^{1/3}. Theoretical & experimental analysis on muscovite mica with a Si₃N₄ tip illustrate the effects of scan overlap. The CRLS model, derived from the Hertz contact mechanics theory, shows that scan overlap is considerable. AFM wear trials on mica under pH 5 conditions legitimize this development, with CRLS readily predicting the additional scan history from scan overlap for the mild wear regime. CRLS theory, however, consistently underestimates severe wear trends, which is to be expected in light of Hertzian principles employed.

Nanometer Structures

Room 308 - Session NS-ThM

Advances in Scanning Probes

Moderator: R. Bennewitz, University of Basel, Switzerland

8:20am **NS-ThM1 Autonomous Atom Assembly***, *R.J. Celotta, J.A. Stroscio, A.P. Fein, S.R. Blankenship, A. Lacaze, J. Cugini*, National Institute of Standards and Technology

The ability to use an STM to move and position atoms with lattice site precision provides us with a quantum workbench to study the effects of quantum confinement and the electronic structure of perfect nanostructures. So far, atomic manipulation has been performed manually, or with rudimentary computer assistance. In this talk, we describe an Autonomous Atom Assembler (AAA), which is an instrument capable of assembling a desired nanostructure from an unknown random collection of atoms without human intervention. It is based on an existing low temperature STM system, with hardware and software extensions. In operation, a dilute coverage of adsorbate atoms is deposited on a clean, flat substrate. The AAA then instructs the STM to image the random adsorbate pattern, identifies the position of each adsorbate atom relative to the substrate lattice, and plans a series of moves to place the available atoms at positions specified in a previously entered diagram. The plan minimizes construction time, follows a set of extensible rules, and allows for error correction. The AAA then instructs the STM to execute the plan and, upon completion, provide an image of the final assembled nanostructure. In our initial trials, Co atoms were deposited to a coverage of 0.003 monolayer on a Cu(111) substrate initially held at 7 K in UHV. Subsequent STM measurements were performed at a 4.3 K sample temperature. Simple confinement structures were autonomously assembled involving tens of atoms. We will report our first results, including the accuracy of positioning, speed of operation, reliability, and scalability of our design. * Supported in part by the Office of Naval Research

8:40am **NS-ThM2 Combined Scanning Force Microscope and Mass Spectrometer**, *A. Wetzel*, University of Basel, Switzerland; *D.-W. Lee*, IBM Research, Zurich Research Laboratory, Switzerland; *R. Bennewitz*, University of Basel, Switzerland; *M. Despont, P. Vettiger*, IBM Research, Zurich Research Laboratory, Switzerland; *Ch. Gerber*, University of Basel, Switzerland; *E. Meyer*, University of Basel, Switzerland

We have constructed a scanning force microscope in ultrahigh-vacuum where the tip position can be switched between the sample surface and a local electrode that serves as entrance for a time-of-flight mass spectrometer. Material shall be picked up at the surface and chemically identified in the mass spectrometer after field-induced desorption from the tip. Tip, force sensor, switch, and local electrode are integrated in one silicon device. We will describe the technical details, proof the concept of the device, and discuss the important requirements to the tip quality. Finally, we will present first experimental results obtained with the new instrument.

9:00am **NS-ThM3 Imaging Semiconducting Samples by Scanning Capacitance Force Microscopy (SCFM) and Scanning Capacitance Microscopy (SCM)**, *K. Kobayashi, K. Kimura, H. Yamada, K. Matsushige*, Kyoto University, Japan

We recently developed scanning capacitance force microscopy (SCFM) based on electrical force detection which is capable of mapping local differential capacitance (dC/dV) without an ultrahigh frequency capacitance sensor. While an electric field alternating at a fixed frequency (f) is applied between a tip and a sample, an induced electrostatic force (ESF) oscillating at its third harmonic frequency (3f) as a differential capacitance (dC/dV) signal is detected by a lock-in technique. SCFM works both in contact mode and dynamic mode. Since the sensitivity of SCFM is inherently high owing to the extremely high force sensitivity in scanning force microscopy (SFM), SCFM can be a high-resolution dopant-profiling technique for semiconducting samples. In this paper, we investigate the imaging mechanisms of SCFM using a silicon test sample having several microfabricated patterns of p-type, n-type and heavily-doped n-type regions. Image contrast changes depending on the applied bias voltage to the sample and the laser light irradiation were discussed. Conventional scanning capacitance microscopy (SCM) imaging were also performed and the results obtained by both techniques are compared and their advantages and limitations are discussed.

9:20am **NS-ThM4 AFM Force Measurements: MEMS Devices for Easy and Accurate Cantilever Spring-Constant Calibration**, *P.J. Cumpson*, National Physical Laboratory, UK; *J. Hedley*, University of Newcastle, UK; *P. Zhdan*, University of Surrey, UK

A value for the spring-constant of Atomic Force Microscope (AFM) cantilevers@footnote 1@ is necessary for the measurement of nanonewton and piconewton forces, which are critical to analytical applications of AFM in the analysis of polymer surfaces, biological structures and organic molecules.@footnote 2@ We have developed compact and easy-to-use micromachined reference artefacts for this calibration. The principal device consists of an array of dual spiral-cantilever springs, each supporting a polycrystalline silicon disc of 170 micrometres in diameter. These were fabricated by a two-layer polysilicon surface micromachining method. Doppler velocimetry is used to measure the fundamental resonant frequency of each device accurately. We call such an array a Microfabricated Array of Reference Springs (MARS). These devices have a number of advantages. Firstly, modelling the fundamental resonant frequencies of the devices is much more straightforward than for AFM cantilevers,@footnote 3@ because the mass and spring functions are isolated in different parts of the structure. Secondly, the spring constant of each spring is in linear proportion to the mass of the device, given that the resonant frequency is measured accurately. The thickness and hence the mass can be measured accurately by AFM or interferometry. These factors lead to much lower uncertainty than previous methods in which spring constant is proportional to the cube of a critical dimensional measurement. The array spans the range from 0.1 N/m to 10 N/m important in AFM, allowing AFM cantilevers to be calibrated easily and rapidly. New devices that extend this range down to around 0.03 N/m, and up to around 80 N/m will also be discussed. @FootnoteText@ @footnote 1@ N A Burnham et al, Nanotechnology 14 (2003) 1-6 @footnote 2@ J Colchero in Procedures in Scanning Probe Microscopies, Ed. R J Colton et al (Wiley, Chichester, UK, 1998)@footnote 3@ C T Gibson et al, Nanotechnology, 7 (1996) 259-262. .

9:40am **NS-ThM5 Thermal Approach to Cantilever Calibration over a 200 kHz Bandwidth**, *G.A. Matei*, Wayne State University; *E.J. Thoreson, N.A. Burnham*, Worcester Polytechnic Institute

A cantilever's stiffness can be determined from an analysis of its thermal distribution spectrum, making use of the equipartition theorem $k = k_{sub B@T}$, where k is the cantilever stiffness and $k_{sub B@T}$ is the thermal energy. We recently showed that it is possible to obtain good values for k, even when the cantilever's resonance is close to the edge of the data acquisition bandwidth, with the formula $k = k_{sub B@TQ@DELTA@}@nu@/(pi@}@nu@}@sub k@)$.@footnote 1@ Here, Q is the quality factor, @DELTA@}@nu@ the frequency resolution of the data acquisition, @nu@}@sub k@ is the resonant frequency, and is the mean-square amplitude at resonance. The initial work was limited to a 30 kHz bandwidth, that is, to cantilevers of stiffness less than approximately 0.4 N/m. Thermal calibration methods are independent of materials properties, coating thickness, cantilever geometry, and the viscosity of the medium, so there is good motivation to extend the methodology to higher bandwidths and thus stiffer cantilevers. We have now expanded the frequency range to 200 kHz, the bandwidth of the preamplifier of our AFM. By monitoring the raw A-B signal with an oscilloscope, then downloading the signal to a computer in order to manipulate the data, we have determined the stiffness of a 180 kHz cantilever to be 3.9 ± 0.2 N/m. By comparing our results for "force-calibrated" cantilevers with the manufacturer's stiffness calculation, we estimate that the accuracy of our method is 5%. By inverting a coated cantilever and repeating the measurement on the uncoated side, we believe that the precision is a similar value. Moreover, consistent with finite-element analyses, we find that the coating can perturb the stiffness by twenty percent. @FootnoteText@ @footnote 1@ Comparison of Calibration Methods for Atomic-Force Microscopy Cantilevers," NA Burnham, X Chen, CS Hodges, GA Matei, EJ Thoreson, CJ Roberts, MC Davies, SJB Tendler, Nanotechnology 14 (2003) 1-6.

10:00am **NS-ThM6 Are V-shaped Atomic Force Microscope Cantilevers Obsolete?**, *J.E. Sader*, University of Melbourne, Australia

The performance of the atomic force microscope (AFM) is underpinned by the mechanical properties of its force-sensing microcantilever. Originally, the AFM cantilever was handcrafted from a thin film of gold, in the shape of a rectangular plate. Shortly after, microfabrication techniques were introduced to facilitate the construction and mass production of AFM cantilevers, and a number of different cantilever geometries were proposed. Of these, rectangular and V-shaped cantilevers have emerged as

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the accepted standards for AFM applications. The V-shaped cantilever was proposed initially as an alternative to the rectangular cantilever, with the explicit aim of minimizing the effects of lateral forces on the deformation of the cantilever. However, the motivating premise that V-shaped cantilevers are more resistant to lateral forces than rectangular cantilevers was never examined. Consequently, in this talk I shall present a detailed comparison of the complementary performance of V-shaped and rectangular cantilevers, with regards to their stability to lateral forces. In so doing, I shall rigorously establish that contrary to accepted thinking and the original intent, use of V-shaped cantilevers will enhance the effect of lateral forces in comparison to rectangular cantilevers. This counterintuitive finding is independent of whether the cantilevers are in contact with a surface or not, and suggests that rectangular cantilevers should be used in preference to V-shaped cantilevers for applications where the effects of lateral forces are to be minimized. This finding strongly contradicts established operating principles of the AFM, which dictate that V-shaped cantilevers should be used to minimize the effects of lateral forces. Consequently, drawing on the findings of this study, a case will be presented for the universal use of rectangular cantilevers in the AFM, which in turn will improve the performance of the instrument while greatly simplifying its operation.

10:20am NS-ThM7 Electronic Properties of Individual Defects in Carbon Nanotubes by Scanning Probe Microscopy, V. Meunier, S.V. Kalinin, R.J. Harrison, A.P. Baddorf, Oak Ridge National Laboratory

Electronic devices based on carbon nanotubes and semiconductor nanowires require development and understanding of quantitative tools for transport measurements at nanoscale dimensions. Scanning Gate Microscopy (SGM) and Scanning Impedance Microscopy (SIM) are both capable of detecting atomic-scale defects in carbon nanotubes. In SGM individual defects are visualized as a decrease in the current through the dc circuit, since defects are depleted for tip voltages that are related to the local electronic structure of the defect. In SIM the local ac potential amplitude and phase are recorded; the defects are manifest as potential drops (back gate regime) or potential minima (tip gate regime). Here, a method for quantitative characterization of the electronic structure of individual defects from SGM and SIM results is presented. The interaction between a carbon nanotube and a point charge is studied using both atomistic first principles calculations and continuum electrostatic methods. The results are compared and extrapolated to real tip geometries in order to simulate the interaction of the scanning tip with an adjacent nanotube. Comparison with experimental data suggests that the gate voltage dependence of the image contrast is a direct measure of the difference in Fermi energies at these defects. The potential of the present approach for the identification of individual defects is discussed.

10:40am NS-ThM8 Real-Space Imaging of the Vortex Lattice in $V@sub 3@Si$ Using Low Temperature Scanning Tunneling Microscopy*, J.A. Stroscio, C.E. Sosolik, M.D. Stiles, National Institute of Standards and Technology; E.W. Hudson, Massachusetts Institute of Technology; S.R. Blankenship, A.P. Fein, R.J. Celotta, National Institute of Standards and Technology

In Type II superconductors, the expulsion of an applied magnetic field from the superconductor, the Meissner effect, is not complete for fields above the lower critical field. In this applied field regime, magnetic flux penetrates the superconductor as quantized vortices that interact through shielding currents. In equilibrium the vortices form a lattice with symmetry, and orientation relative to the crystallographic axes, determined by microscopic electronic properties. In this talk we present low temperature scanning tunneling microscopy measurements of the structural evolution of the vortex lattice in a single-crystal $V@sub 3@Si$ sample. Large-scale conductance maps obtained at 2.3 K provide a real-space image of the vortex lattice formed with a magnetic field applied parallel to the [001] crystal axis. Atomic resolution topography of the $V@sub 3@Si$ (001) surface shows the underlying Si sublattice and allows for a determination of the orientation of the measured vortex lattice relative to the underlying crystal axes. The conductance maps reveal a change in the symmetry of the vortex lattice from hexagonal to nearly square over the field range of 0 T to 4 T. A strong anisotropy in the long-range translational order of the vortex lattice is observed near the transition field of 4 T. These observations give evidence for nonlocal electrodynamics in the vortex-vortex interactions of this Type II superconductor. Calculations that account for the role of these nonlocal effects in determining the structure and symmetry of the vortex lattice are presented and compared to our experimental results. * This work is supported in part by the Office of Naval Research.

11:20am NS-ThM10 Adatom Hopping Induced by Tunneling Electrons: Br on $Si(100)-(2x1)$, K.S. Nakayama, E. Graugnard, J.H. Weaver, University of Illinois at Urbana-Champaign

Tunneling electrons from the tip of a scanning tunneling microscope can be used to induce adatom hopping on Br-terminated $Si(100)-(2x1)$ at low current and without voltage pulses. Hopping does not occur when electrons tunnel from a sample to a tip. The threshold energy is +0.8 V, and tunneling spectroscopy shows antibonding Si-Br states 0.8 eV above the Fermi level. Electron capture in these states is a necessary condition for hopping, but repulsive adsorbate interactions that lower the activation barrier are also required. Such interactions are strong near saturation for Br but are insufficient when the coverage is low or when Br is replaced by Cl.

11:40am NS-ThM11 Elucidation of the Electronic Properties of Isolated Alkanethiolate-Passivated Undecagold Clusters by Low Temperature Scanning Tunneling Microscopy and Spectroscopy, S.U. Nanayakkara, R.K. Smith, T.P. Pearl, B.A. Mantooth, P.S. Weiss, The Pennsylvania State University; G. Woehrle, J.E. Hutchison, University of Oregon

We have studied the electronic properties of isolated, octanethiolate-stabilized undecagold clusters [$Au@sub 11@(S(CH@sub 2@)@sub 7@CH@sub 3@)@sub 10@]$] using low temperature scanning tunneling microscopy (STM) and spectroscopy (STS). The clusters, $d@sub CORE@ = 0.8 \pm 0.2$ nm, were immobilized by inserted dithiol molecules in an alkanethiolate self-assembled monolayer (SAM) on Au(111). The clusters were synthesized in solution by ligand exchange of $Au@sub 11@(PPh@sub 3@)@sub 8@Cl@sub 3@$ with octanethiol, resulting in a complete octanethiolate ligand shell, and were subsequently deposited upon a SAM. The geometry of the STM tip-vacuum-gold cluster-SAM-Au(111) assembly can be modeled as a double barrier tunnel junction, which may give insight into controlling the movement of single or small numbers of electrons. Discrete quantum energy levels are more evident in this cluster size range where the atomic character of the metal is prominent. We have observed Coulomb blockade of these clusters at 4 K. The current-voltage characteristics show uneven spacing between adjacent current steps, showing quantized energy states. The observed, large zero-conductance gaps result from quantum size effects, where the bound octanethiolate ligand shell further reduces the free volume in which the electrons can move. This study assesses the impact of sub-nanometer sized clusters on single electron transport properties, enlightening the future of nanoscale electronics.

Nanometer Structures

Room 317 - Session NS+BI-FrM

Nanotechnology and Biology

Moderator: R.J. Hamers, University of Wisconsin-Madison

9:40am **NS+BI-FrM5 Interaction of Fluorescent Molecules with Metallic Nanoparticles Mediated by Biospecific Interactions, V.H. Perez-Luna, K. Aslan, I. Severcan**, Illinois Institute of Technology

Metallic nanoparticles affect the emission characteristics of fluorophores located in their proximity. Here we exploit this strong influence in a system where gold nanoparticles are functionalized with biotin. Preparation of biotinylated gold nanoparticles is performed in the presence of a nonionic surfactant to ensure their stability. The interaction of these biotinylated gold nanoparticles with Alexa488-labeled anti-biotin in solution was studied by optical absorption spectroscopy and fluorescence spectroscopy. It was found that reduction or enhancement of fluorescence emission could result when Alexa488-labeled anti-biotin interacted with biotinylated gold nanoparticles. This depended on the surface coverage of biotin groups, the concentration of antibody and the concentration of biotinylated gold nanoparticles. Introduction of soluble biotin to dissociate the bound antibodies from the surface of the nanoparticles reversed the signals observed previously. These observations can be explained in terms of the competing effects that metallic nanoparticles can have on emission of fluorescence. Quenching of fluorescence can occur when the fluorophores are in close proximity to the metallic surfaces. However, metallic nanoparticles can also enhance the excitation intensity due to concentration of the incident field in the vicinity of the nanoparticles. Additionally, metallic surfaces can also provide additional pathways for radiative decay of the fluorophores. These concepts will have important implications for novel materials in fluorescence detection.

10:00am **NS+BI-FrM6 Real-Time, Label Free Biosensing using Immobilized Gold Nanoparticles: Influence of Nanoparticle Size on Sensor Performance, N. Nath, A. Chilkoti**, Duke University

We recently demonstrated a label-free optical sensor to quantify biomolecular interactions in real-time that exploits the surface plasmon resonance effect exhibited by noble metal nanoparticles (nanoSPR). The sensor monitors changes in the extinction spectrum of a monolayer of gold nanoparticles on glass as a function of biomolecular binding. We have previously shown that 13 nm diameter gold nanoparticles can monitor the binding of streptavidin to biotin with a detection limit of 16nM. The performance of the biosensor is controlled by the size, shape and dielectric constant of the metal nanostructures, and their interparticle spacing. As a first towards optimization of the nanoSPR sensor, we investigated the size of gold nanoparticles on sensor performance. Monodisperse gold nanoparticles were chemically synthesized with diameters ranging from 12 nm to 50 nm. The extinction spectrum of the monolayers of gold nanoparticles of all sizes exhibited both a red shift as well as an increase in the extinction at peak wavelength as a function of bulk solution refractive index. However, sensitivity, defined as change in extinction per unit change in bulk refractive index, increases with an increase in particle size and reaches a maximum value of 1.42 for a particle size of 39 nm. Second, the sensing volume of the immobilized gold nanoparticles, defined as the distance from the surface within which a bulk refractive index change will result in a change in the optical signal, increases with particle size and peaks for 39 nm diameter nanoparticles. Based on these results, an optimized sensor was fabricated using 39 nm gold nanoparticles, and its detection limit for biotin-streptavidin binding was found to be ~1 nM. NanoSPR on a chip is attractive for biosensing because of simple solution based assembly and ability to measure extinction spectrum using widely available UV-vis spectrophotometers.

10:20am **NS+BI-FrM7 Ultrasensitive Nanowire Sensor for Drug Discovery and Medical Diagnostics, W. Wang**, Harvard University

Semiconductor nanowires represent a novel class of nanostructured materials with a wide range of future applications from molecular electronics to biotechnology. Using appropriate fabrication procedures, our group has previously demonstrated that field-effect transistors (FETs) made from p-type Si nanowires possess electronic characteristics exceeding that of conventional planar devices. This outstanding electronic property makes nanowire FETs ideal transducers in a sensor system with label-free, real-time detection capability. Furthermore, sensors made from Si nanowires offer additional advantages over other type of sensors including the ease to

differentially modify many nanowires for multiplexed sensing, the potential to be very small and inexpensive, and most importantly the unparalleled extreme sensitivity to the point where single molecule detection is possible. With successful chemical modification to covalently immobilize biological receptors onto the surface of nanowires, we showed that a nanowire FET can be configured into a nano-scale sensor and the binding of charged ligands to the receptors generates specific electrical responses in a quantitative manner. We first applied this strategy to develop a sensitive detector for prostate cancer by measuring the levels of PSA, a marker for prostate cancer. The sensor was shown to detect PSA as low as 0.025 pg/ml (7fM). In addition to medical diagnostics, the combined advantages of label-free detection and extreme sensitivity offer a unique opportunity to configure the nanowire sensors into a drug discovery platform. Using Abl kinase/ATP/Gleevec as a model pathological system (in chronic myeloid leukemia), we have demonstrated the possibility to visualize drug action, or small molecule/protein interactions in real time. Lastly, because of the high sensitivity inherent to the nanowire sensors, individual binding/unbinding events of single molecules can be resolved electrically.

10:40am **NS+BI-FrM8 Nanopores in Ultrathin MOS-compatible Membranes for Electrical Detection of DNA, T. Kim, J. Heng, V. Dimitrov, C. Ho**, University of Illinois at Urbana-Champaign; **A. Kornblit, F. Klemens, J. Miner, W. Mansfield, C. Pai, T. Sorsch**, New Jersey Nanotechnology Consortium; **G. Timp**, University of Illinois at Urbana-Champaign

We are developing a revolutionary type of silicon integrated circuit that incorporates MOS technology with an on-chip nano-pore mechanism for directly sensing the electrical activity of bio-molecules such as ions, proteins or DNA. The electronic detection of biological analytes could have several advantages over the conventional scheme, fluorescent microscopy, which is used so prevalently in biology to discriminate the experimental outcomes. For example, if each analyte has a characteristic signature, then an electronic biosensor could facilitate the analysis of the data by eliminating the need for sensitive dyes, thereby improving the dynamic range for detection. We have recently discovered a method to produce ~1-2nm diameter pores (a size comparable to the secondary structure of a protein) in membranes made from materials such as Si, SiO₂@sub 2@, and Si@sub 3@N@sub 4@ that are compatible with MOS fabrication technology. We have adopted this method to create nano-pores spanning a high quality ~2-5nm thick SiO₂@sub 2@ membrane that constitutes part of the gate electrode in a Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) amplifier. Here, we report on the fabrication of nanometer-scale pores in MOS compatible materials using a high voltage, tightly focused electron beam, and on time-resolved measurements of the transport of 100bp to 1500bp DNA through a range of pore diameters (2-8nm) and membrane thicknesses (2-30nm).

11:00am **NS+BI-FrM9 Electrically Switchable Nanostructured Superhydrophobic Surfaces, J.A. Taylor**, New Jersey Nanotechnology Consortium; **T.M. Schneider, S. Yang**, Bell Laboratories, Lucent Technologies; **A. Kornblit**, New Jersey Nanotechnology Consortium; **T.N. Krupenkin**, Bell Laboratories, Lucent Technologies

Dynamically switchable nanostructured surfaces are investigated. Behavior of liquids on these surfaces is studied both experimentally and theoretically. Three major states of a liquid drop on these surfaces are demonstrated. The states include highly mobile rolling ball, immobile droplet, and complete wetting state. The transitions between these states were dynamically induced by applying a voltage between a liquid and a nanostructured substrate. Droplet contact angle was measured as a function of applied voltage and nanostructured layer geometry. The obtained results show quadratic dependence of the cosine of the contact angle on voltage, which is in good agreement with the typical electrowetting behavior. The details of interaction of liquids with the nanostructured layer were investigated using SEM technique. The proposed approach potentially allows novel methods of manipulating microscopically small volumes of liquids. This includes essentially frictionless liquid transport, the ability to selectively immobilize the droplets at any given time or position, as well as dynamic control over the penetration on liquids through the nanostructured layer. The obtained results potentially open new and exciting opportunities in microfluidics, chemical microreactors, bio/chemical detection, thermal management of microelectronics, bio-optics, and many other areas.

11:20am **NS+BI-FrM10 Engineering Information Processing in Biological Systems, R.H. Blick**, University of Wisconsin-Madison **INVITED**

The key aspect of this work is to present methods for understanding and engineering information processing in nanoscale biological systems. The

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systems we are focusing on are nanometer-sized ion channels integrated in high frequency circuits. The ion channels are embedded in bilipid membranes, which are brought to microstructured glass chips for direct transport measurements. Recording the passage of ions is successfully performed and first results on high-frequency response are shown.

Semiconductors

Room 321/322 - Session SC+NS-FrM

Low Dimensional Structures and Amorphous Silicon

Moderator: A.C. Gossard, University of California, Santa Barbara

8:20am **SC+NS-FrM1 Self-Organized Template Formation for Quantum Dot Ordering**, *R. Noetzel*, Eindhoven University of Technology, The Netherlands **INVITED**

The realization of semiconductor quantum dot arrays and networks in well-defined lateral arrangements is essential for the development of future quantum functional devices. We have successfully created these kinds of networks by self-organized anisotropic strain engineering of (In,Ga)As/GaAs templates for the ordering of InAs quantum dots by local strain recognition: On GaAs (100) substrates, during molecular beam epitaxy of a strained (In,Ga)As/GaAs superlattice, elongated (In,Ga)As quantum dots develop into very uniform and long quantum wire arrays with a well-defined lateral periodicity. Quantum wire formation relies on the anisotropic adatom surface migration and In desorption during annealing of the layers of elongated quantum dots after capping with a thin GaAs layer. The accumulation and improvement of the uniformity of the generated anisotropic strain field in superlattice growth provides a well-defined template for the ordering of InAs quantum dots grown on top in one-dimensional arrays. On high-index GaAs (311)B substrates, strain induced growth instability of (In,Ga)As layers occurs to form a matrix of closely packed cells. The related strain distribution constitutes a uniform template for the full control of InAs quantum dot nucleation in a two-dimensionally connected network. Excellent structural perfection and optical properties are established for these ordered InAs quantum dot arrays by atomic force microscopy, high-resolution X-ray diffraction, and photoluminescence spectroscopy. Temperature dependent photoluminescence measurements reveal efficient carrier transfer from the templates, which themselves are distinct one- and zero-dimensional quantum nanostructure arrays, to the quantum dots and within the quantum dot arrays. Hence, self-organized anisotropic strain engineering provides a unique route for the realization of well-defined and functional quantum dot arrays and networks of high quality.

9:00am **SC+NS-FrM3 Self-Assembly of Nanostructures in GaAs/InAs and GaAs/GaSb Multilayer Structures**, *C.A. Pearson, C. Dorin, J. Mireckii Millunchick, Y. Chen, B.G. Orr*, University of Michigan, Flint

Reproducibly obtaining regular arrays of phase-separated material is a promising way to acquire low dimensional structures such as quantum dots or wires. Short period superlattice (SPS) structures, where each layer is approximately one or two monolayers thick, can spontaneously phase separate under certain growth conditions resulting in compositional modulations. The appearance of lateral composition modulation is correlated to roughening of the surface front. To further elucidate this progression, in situ scanning tunneling microscopy (STM) was used to examine SPS structures at integral and fractional periods, where one period consists of 2 monolayers (ML) of GaAs followed by 2 ML of InAs or GaSb. For both integral and fractional periods, the surfaces are quite distinct. The as-grown InAs surface is decorated with anisotropic islands that exhibit a (2x4) reconstruction upon a terrace with a (nx3) reconstruction. The GaAs terminated surfaces are characterized by flat mesa structures surrounded by deep trenches. With increasing number of periods, both surfaces evolved towards greater long scale roughness. Furthermore, the islands (InAs terminated) or trenches (GaAs terminated) become larger and show a preferential lateral arrangement with a characteristic separation in the [110] direction of ~20 nm, which corresponds to the modulation wavelength observed using other techniques. Similar results are also observed in the GaAs/GaSb structure where islanding of GaAs is observed in a GaSb matrix. These results are consistent with continuum perturbation models that predict the coupling of morphological and compositional instabilities under the appropriate circumstances.

9:20am **SC+NS-FrM4 Tuning of the Electronic Properties of Self-assembled InAs/InP(001) Quantum Dots by Rapid Thermal Annealing and Low-energy Ion Implantation**, *C. Dion*, École Polytechnique de Montréal, Canada; *C. Ni Allen, S. Raymond, P.J. Poole*, National Research Council, Canada; *F. Schiettekatte*, Université de Montréal, Canada; *R.A. Masut, P. Desjardins*, École Polytechnique de Montréal, Canada

We have investigated the effect of post-growth rapid thermal annealing on the low temperature photoluminescence (PL) spectra of self-assembled InAs/InP(001) quantum dots (QD) grown by chemical beam epitaxy (CBE) and metal-organic vapor phase epitaxy (MOVPE). Annealing temperatures T_{a} and times t_{a} ranged from 650 to 800 °C and 30 to 210 s, respectively. As-grown samples are characterized by a broad emission peak centered near 800-900 meV arising from the e1-hh1 transition of an ensemble of QDs and a narrow peak near 1100 meV from radiative recombination in the wetting layer. Detailed analysis of the QD PL emission reveals that it is composed of up to 9 peaks corresponding to families of dots emitting at different energies. A blueshift of the QD transitions, resulting from intermixing, is observed upon annealing. It increases with T_{a} and t_{a} ; blueshifts of up to 90-100 meV are obtained for annealing time of 210s at 800 °C. While the PL emission energies of the various QD families shift at different rates upon annealing, their width remains constant. This behavior is consistent with inhomogeneous broadening dominated by monolayer height fluctuations in InAs/InP(001) dots. In order to obtain larger blueshifts, we studied the effect of introducing point defects into thick InP cap layers, either by growing InP at low temperature or by implanting P at energies sufficiently low to insure that the InAs QDs are not damaged. Such point defects, located far from the QDs, dramatically increase diffusion rates; shifts of up to 250 meV have been obtained following annealing at 765 °C for 90 s.

9:40am **SC+NS-FrM5 Anisotropic Stress Relaxation and Ordering of InAs/GaAs Quantum Dot Superlattices**, *W. Ye, M. Reason, X. Weng, R.S. Goldman*, The University of Michigan

Recently, self-assembled quantum dot (QD) superlattices (SLs) have shown significant promise for a wide range of electronic and optoelectronic device applications. In general, self-assembled QD formation is driven by the elastic relaxation of stress via island nucleation. The vertical stacking of QDs is often explained by the preferred nucleation of islands at strain energy minima directly above buried dots. However, the mechanisms of lateral ordering of QD arrays are the subject of continued debate. For example, anisotropic lateral alignment of QDs has been observed in a number of materials systems. A significant remaining question concerns the relative effects of buffer layer patterning and anisotropic stress relaxation on this lateral QD alignment. Therefore, we have examined the patterning effects of buffer layers, as well as the stress relaxation process during the growth of stacked QDs. Our QD SLs consisted of 2.6 ML InAs and 5 nm GaAs grown by molecular beam epitaxy at 500°C. Prior to QD deposition, GaAs buffer layers were grown at 580°C and/or 500°C. During QD growth, reflection high energy electron diffraction (RHEED) reveals a streaky to spotty pattern transformation, typical of the Stranski-Krastanov (S-K) growth mode transition. However, simultaneous wafer curvature measurements using multi-beam optical stress sensor (MOSS) reveal that stress relaxation occurs after the S-K growth mode transition is complete. Ex-situ atomic force microscopy measurements indicate a preferential alignment of QDs along the [-110] direction. This anisotropic alignment is enhanced as the number of SL periods increases and may be due to pre-patterning by the 500°C buffer layer. We will discuss the relative roles of buffer layer patterning and anisotropic stress relaxation on QD ordering. This work was supported in part by DOE (Photovoltaics Beyond the Horizon Program), ARO (MURI Program), and NSF (Nanoscale Exploratory Research Program).

10:00am **SC+NS-FrM6 Ge Island Nucleation on Large-Miscut Si(001) Surfaces**, *K. Ohmori, Y.L. Foo, S. Hong, J.G. Wen, J.E. Greene, I. Petrov*, University of Illinois at Urbana-Champaign

We study self-organized growth of Ge nanostructures on Si surfaces with large off-[001]-axis miscut as a function of the tilt angle θ and in-plane azimuth angle ϕ with respect to the [100] direction. The off-axis surfaces were fabricated using focused ion beam (FIB) to precisely pattern a variety of structures such as trenches, concave cones, and square-pyramids on Si(001) surfaces. During the FIB processing, the Si(001) substrates were covered with 200-nm-thick protective SiO₂ films. A 50-nm-thick Si buffer layer was grown at 800°C by ultrahigh vacuum gas-source molecular beam epitaxy using Si₂H₆ precursor prior to Ge deposition at 600°C using Ge₂H₆. The nominal thickness of the Ge layer is about 7 ML. Diverse Stranski-Krastanov growth

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modes (Ge domes, elongated islands, and nanowires) were observed as a function of θ and ϕ , which we attribute to differences in anisotropic-strain relief mechanism. While on a vicinal (001) surface ($\theta = 0.3^\circ$), dome-shaped Ge islands with a density of $30.9 \mu\text{m}^{-2}$ are formed, the island density increases by 30% on a surface with $\theta = 5^\circ$ for all ϕ -values. In the range of $\theta = 10$ to 20° , elongated island shapes emerge in directions near $\phi = 45^\circ$ ($n = 1, 3, 5, 7$), while at $\phi = 90^\circ$ ($n = 0, 1, 2, 3$) island nucleation is suppressed. With $\theta \geq 25^\circ$, Ge nanowires with a length of about $2 \mu\text{m}$ are formed on planes with $\phi = 45^\circ \pm 15^\circ$ ($n = 1, 3, 5, 7$).

10:20am **SC+NS-FrM7 Bond-Centered Hydrogen in Amorphous Silicon: New Infrared Studies**, *J.-F.T. Wang*, Vanderbilt University; *G. Lüpke*, The College of William and Mary; *L.C. Feldman*, *N.H. Tolk*, Vanderbilt University
Recent infrared absorption spectroscopy measurements taken at 77 K on initially hydrogen free amorphous silicon following hydrogen implantation at low temperature, exhibit an absorption line associated with the bond-centered (BC) hydrogen local vibration stretching mode at 1993 cm^{-1} . This line, newly observed in amorphous silicon, appears at the same wavelength seen in crystal silicon following hydrogen implantation at LN temperatures.^{1,2} These results indicate that the bond-center (BC) hydrogen defect structure can form in amorphous silicon as well. The experimental data give insight into recent molecular dynamic simulations involving hydrogen's role in the amorphous-to-nanocrystalline phase transition in amorphous silicon.³ In both the crystalline and amorphous case, the 1993 cm^{-1} line disappears when the samples are annealed to room temperature. However only in the crystalline silicon case does the migrating hydrogen reappear in other IR-active defect sites.^{1,2} ¹M. Budde, G. Lüpke, C. Parks Cheney, N. H. Tolk, and L. C. Feldman, Phys. Rev. Lett. 85, 1452 (2000). ²B. Holm, K. Bone Nielsen, and B. Bech Nielsen, Phys. Rev. Lett. 66, 2360 (1991). ³Saravanapriyan Sriraman, Sumit Agarwal, Eray S. Aydil & Dimitrios Maroudas, Nature (London) 418, 62 (2002).

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