Nanometer-Scale Science and Technology
Room Exhibit Hall C&D - Session NS-TuP

Nanometer Scale Science and Technology Poster Session

NS-TuP1 Free-standing Nanosheets from Cross-Linked Biphenyl Self-Assembled Monolayers, *W. Eck,* Universtät Heidelberg, Germany*; A. Küller, M. Grunze,* Universität Heidelberg, Germany*; B. Völkel,* ***A. Gölzhäuser,*** Universität Bielefeld, Germany

Self-assembled monolayers composed of biphenyl units are cross-linked by electron irradiation. These monolayers can be released from the underlying surface by dissolution of the substrate or by scission of the anchor group-substrate bonds. This way, free-standing nanosheets with the thickness of a single molecule and lateral dimensions in the micrometer range are obtained. Gold nanoparticles have been deposited on the sheets and successfully imaged by electron microscopy suggesting their use as substrates for microscopy applications.

NS-TuP2 Pulse Thermal Processing of FePt Thin Films, ***A.C. Cole***, *G.B. Thompson,* University of Alabama*; R.D. Ott,* Oak Ridge National Laboratory*; J.W. Harrell,* The University of Alabama

The L1@sub 0@ phase of FePt is a candidate material for next generation magnetic storage because of its high magnetocrystalline anisotropy. When FePt is sputter-deposited onto an ambient temperature substrate, it adopts a metastable solid-solution face-centered-cubic phase that is superparamagnetic. A subsequent anneal is required to chemically order FePt into the L1@sub 0@ phase with its superior magnetic recording properties. A consequence of conventional annealing is grain growth in the film, which is detrimental to increasing areal storage density. We report the use of multiple pulsed-thermal-processing with a high density infrared plasma light source at exposure times of 100 and 250 ms to chemically order FePt films. Upon ordering, no grain growth of the 15 nm diameter columnar grains was observed in 100 nm thick specimens. As the thin film thickness was decreased, grain growth became more prevalent for similar processing conditions. Moreover, for the smaller grain sizes, we observed a strong evolution of texture upon ordering. The morphology of the films pre- and post- processing has been characterized using high-resolution TEM and XRD. Magnetrometry of the samples has also been performed. The results of this work will address the consequences of pulsed-thermal-processing on phase and morphological stability at the nanometer-scale.

NS-TuP3 Etch of Sub-Micron High Aspect Ratio Holes in a Bilayer of SU-8/PMMA Resist Stack for Photonic Crystal Devices, ***J.H. Sung***, *K.J. Lim, B.H. O,* Inha University, Korea*; Y.H. Choe,* LG Electronics Institute of Technology, Korea

Sub-micron hole array in a bilayer of SU-8 for core and poly-methyl-metacrylate (PMMA) for clad have been successfully etched for the fabrication of photonic crystal (PC) structures. In the PC waveguides, the etched holes need to be extended into the cladding layer to ensure the proper optical characteristics. The fabrication started from coating multiple materials on a glass substrate to form a multi-layer of hydrogen silsesquioxane (HSQ)/PMMA/SU-8/PMMA. Using a nano-patterned stamp, PC patterns are imprinted into the top HSQ layer at room temperature. After the pattern transfer by a dry etch in our inductively coupled plasma (ICP) system, Cr sputtering was followed for a lift-off process. The Cr pattern was successfully formed on the top of 1-um-thick SU-8 and 2-um-thick PMMA resist stack. Using this Cr pattern as a hard mask, sub-micron holes are etched also in the ICP etcher. Various gas chemistries are attempted to achieve vertical profiles and a high aspect ratio. The best etch conditions for a PC structure with high aspect ratio and vertical side-wall profile will be discussed.

NS-TuP4 An Innovative Approach to Nanoscale Device Fabrication, ***E.A. Akhadov***, *A.H. Mueller, M.A. Hoffbauer,* Los Alamos National Laboratory

A recently developed technology exclusive to LANL, called Energetic Neutral Beam Lithography/Epitaxy (ENABLE), offers exceptional opportunities for producing nanoscale structures and for synthesizing thin film materials. ENABLE utilizes reactive neutral atomic species (O and N) having kinetic energies comparable to chemical bonds strengths (a few eV) for etching very high-aspect-ratio features into polymers and for growing oxide and nitride thin films at low temperatures. Using energetic oxygen atoms, numerous nanoscale structures have been fabricated into polymer films that contain sub-100 nm features with very high aspect ratios (in some cases >35:1). For example, using a nanosphere-defined mask a polyimide film was etched to form a periodic array of 5.4 micron tall, 250 nm diameter pillars. As a novel application, nanoscale polymer templates can be fabricated and used for growing nitride (AlN, GaN, etc.) and oxide (Al@sub 2@0@sub 3@, SiO@sub 2@, etc.) structures. This novel fabrication approach can easily be expanded to make 2- and 3-dimensional structures and devices with multiple functionalities. The latest results utilizing ENABLE for producing photonic crystals, MEMS and NEMS devices, microfluidic channels, and novel electronic devices will be discussed.

NS-TuP5 Compositional and Structural Characterization of Tungsten Nanostructures Produced by Electron Beam-Induced Deposition, ***K.L. Klein,*** University of Tennesse & ORNL*; S.J. Randolph, P.D. Rack,* University of Tennessee*; M.L. Simpson,* University of Tennessee & ORNL

Electron beam-induced deposition (EBID) is an emerging technique for the synthesis of nanostructures and nanopatterning. The high degree of precision associated with EBID, (i.e. precise location, size, and shape) makes it a prime candidate for a wide variety of applications ranging from fiber tips for field emission sources to lithography mask repair strategies. Furthermore, a wide array of materials - as governed by the choice of precursor gas - can be deposited by EBID, thus adding to the versatility of the technique. As is the case with all deposition processes, it is critical to be able to control the composition and structure of the deposited material by varying simple process parameters. Thus far there has been very little characterization of the chemical composition and internal structure of EBID materials. Previous results have suggested a significant incorporation of impurities into the deposited material. The deposition conditions as well as precursor composition can impact the resulting chemical composition and nanostructural properties of the deposit. In order to better control these deposit properties, we report on the effects of beam energy, beam current, and localized precursor pressure on tungsten nanostructures deposited by EBID from a tungsten hexafluoride precursor. The results of high resolution TEM, STEM, and EDS on as-deposited tungsten nanostructures will be reported. In addition, the effects of post-deposition processes, such as thermal treatments will be discussed.

NS-TuP6 Formation of Nanometer-scale Structures Based on a Plasma Ashing and Lift-off Technique, ***G.-S. Kim***, Sungkyunkwan University, Korea*; Y.-H. Roh,* Sungkyunkwan University, Korea, Republic of Korea

Realization of nano- and/or bio-electronic devices requires the formation of nanometer-scale structures. Recently the fabrications of structures with a nano gap dimension have been demonstrated by using advanced techniques such as electron-beam lithography, focused ion beam lithography, or advanced optical lithography. However, these techniques are very slow, and moreover require a high production cost. Recently, our group proposed the new technique to overcome a resolution limit of an optical lithography for forming nanometer-scale structures. The technique utilizes a well known and a well established processing technique known as a photoresist (PR) ashing. In this technique, the minimum linewidth can be formed by ashing the PR pattern defined by the conventional optical lithography. In this work, we further developed this technique to form the various shapes of nanometer-scale structures including the line-and-space pattern and nanometer-scale holes. In this particular case, we used a negative PR (PMER) instead of a conventionally used positive PR since the final patterns of PMER after treating the ashing process result in the high aspect ratio, reversal echelon formation and excellent property for fine pattering in general. In turn, the lift-off step that is required to form the highly aligned nanometer-scale structures can be easily followed. Based on the current investigation, we found that various types of nanometer-scale structures can be easily formed using semiconductor, metal and insulator materials. These results may open the possibilities to fabricate the unique tools for the vertical-type field effect transistors and highly aligned emitters.

NS-TuP7 Si Nanoclusters Embedded in SiO@sub 2@ Layers Produced by Reactive RF Sputtering, *E. Sanchez-Meza,* ESFM-IPN, Mexico*;* ***A. Garcia-Sotelo***, *M. Melendez-Lira, A. Mendoza-Galvan, S. Jimenez-Sandoval,* Cinvestav-IPN, Mexico

The production of silicon nanonoclusters is an active topic of research because the possibility to produce efficiently light on a silicon based material. We have taken advantage of the morphologic characteristics of the films deposited by the sputtering technique to produce silicon nanoparticles. We have grown silicon nanoclusters embedded in SiO@sub 2@ layers employing reactive RF sputtering. Different partial pressures of Ar/O@sub 2@ were employed to produce the plasma, a 99.999 % pure silicon disk was employed as target. Samples were deposited on substrates of silicon (100) and commercial glass at 400 °C. Samples were characterized

by X-ray diffraction, atomic force microscopy and room temperature infrared, ellipsometry, photoluminescence and Raman spectroscopies. X ray diffractograms shown that samples grown on silicon present a crystalline structure while films grown on glass are amorphous. Atomic force microscopy shown in both cases the presence of ellipsoidal mounds with axis lengths around 100 nm. Raman spectroscopy presents Raman shifts located at 470 cm@super -1@ due to Si-nanoclusters. Ellipsometry results indicated, in good agreement with the growth procedure, that sample structure correspond to a a-Si+c-Si layer of around 10 nm embedded in layers of SiO@sub 2@. Our results shown that reactive sputtering has a good potential to produce, at low cost, uniform nanoclusters. @FootnoteText@ @footnote 1@work partially funded by CONACyT-México.

NS-TuP8 Recent Lithography Results from the Digital E-beam Array Lithography (DEAL) Concept, ***W.L. Gardner***, *L.R. Baylor,* Oak Ridge National Laboratory*; X. Yang,* University of Tennessee*; R.J. Kasica, D.K. Hensley,* Oak Ridge National Laboratory*; S.J. Randolph, R.B. Rucker, D.C. Joy, P.D. Rack, S. Islam, B. Blalock,* University of Tennessee

The Digital E-beam Array Lithography (DEAL) concept is currently under development at Oak Ridge National Laboratory (ORNL). This concept incorporates a digitally addressable field emission array built into a logic and control integrated circuit to function as the write head for a massively parallel e-beam lithography tool. Each field emission device comprises three electrodes separated 1 µm from each other by SiO2. The first electrode functions as the cathode and contains a single vertically aligned carbon nanofiber as the field emitter. The second is an extraction aperture and the third is an aperture functioning as an electrostatic focusing lens. Field emission and focusing tests on prototype devices demonstrated that the emission follows Fowler-Nordheim characteristics, the beams can be focused as anticipated from numerical simulations, and the extraction and focus apertures in well-aligned devices collect less than 1% of the emitter current. Preliminary lithographic results on PMMA coated substrates demonstrated that variations in linewidth measured as a function of the focus lens voltage are in agreement with device modeling. Recently, we obtained the capability to fabricate thick electrodes, which, based on model results, should provide better focusing and depth of field. Furthermore, progress has been made to obtain better aperture alignment and fabricate individually addressable cathodes. Our research objective is to demonstrate lithography using a full 3x3 array of operating devices. We will discuss our recent results in detail as well as ongoing work to achieve <100-nm linewidths and full array implementation.

NS-TuP9 Characteristic of Carbon Nanotubes Synthesized by Pin-to-Plate Type Atmospheric Pressure Plasma Enhanced Chemical Vapor Deposition at Low Temperature, ***S.-J. Kyung***, *J.H. Lee, C.-W. Kim, M. Voronko, G.Y. Yeom,* Sungkyunkwan University, Korea

In this study, carbon nanotubes (CNTs) were grown on glass substrates coated with NiCr by an atmospheric pressure plasma enhanced chemical vapor deposition and their structural and electrical characteristics were investigated as a possible application to the field emitter of field emission display (FED) devices. NH3 gas flow rate (150sccm~ 270sccm) in He/C2H2/NH3 and the substrate temperature (400~500ï,°C) were varied and the increase of NH3 flow rate to 270sccm and the increase of growth temperature to 500ï,°C increased the length of the grown CNTs and decreased the diameter of the CNTs. The ratio of defective carbon peak to graphite carbon peak of the CNTs grown at 500ï,°C with 270sccm of NH3 measured by fourier transform(FT)-Raman was 0.772. When field emission properties were measured, the turn-on field was 3.5V/um and the emission field at 1mA/cm2 was 5.25V/ um.

NS-TuP10 A Method of Coating and Implanting Carbon Nanotube with Iron Nanoparticles by Inductively Coupled Plasma, ***J.S. Kim***, *G.H. Kim, C.I. Kim, O.J. Yoon, J.K. Jung,* Chungang University, Korea

We describe a new method of coating and implanting Single-Walled Carbon Nanotube with Iron Pentacarbonyl(FeCo@sub 5@) using Inductively Coupled Plasma(ICP). We control the pressure of chamber by hydrogen gas. First, Iron Pentacarbonyl(FeCo@sub 5@) in bubbler was evaporated by heating. Second, Plasma treatment process was performed with hydrogen gas and the evaporated Iron Pentacarbonyl(FeCo@sub 5@), at rf-bias voltage. The result of this work shows Fe nanoparticles coated and implanted on Single Walled Carbon Nanotube(SWCNT). The morphology and structure was investigated by scanning electron microscopy (SEM), transmission electron microscory(TEM), and energy dispersive x-ray(EDX).

NS-TuP11 Carbon Nanotube Copolypeptide Bionanocomposites, ***C. Lovell***, University of Virginia*; E. Worthington,* University of California, Santa Barbara*; T.J. Deming,* University of California, Los Angeles*; G.D. Stucky,* University of California, Santa Barbara*; J. Kang, K.E. Wise,* National Institute of Aerospace*; J.S. Harrison,* NASA Langley Research Center*; J.M. Fitz-Gerald,* University of Virginia*; C. Park,* National Institute of Aerospace

Due to their helical structures, several biopolymers exhibit high shear piezoelectricity. Unfortunately, few natural biopolymers exhibit adequate physical properties to endure practical utilization of their sensing capabilities. Thus, this investigation seeks to explore the shear sensing potential of a synthetic biopolymer. By combining peptides and polymers, synthetic polypeptides should bridge the gap between expensive, functional peptides and inexpensive, less functional polymers. Further augmentation of their electroactive potential and mechanical properties can be achieved by addition of carbon nanotubes (CNTs) to form a nanocomposite material with very low density . Functional characterization of drop-casted thin films was performed, including electrical and dielectric measurements, as well as mechanical tests. It was found that several properties, including conductivity, permittivity, tensile strength, Young's modulus, and toughness increased with SWNT loadings. However, one of the main limiting factors in achieving the best performance of CNT-polymer composites is a sharp increase of material viscosity at high concentrations (5-6 wt.%) of CNTs, which limits the capabilities of conventional fabrication techniques. In order to exploit the unique properties of CNTs in macroscopic composites, significant progress has to be made in the development of new advanced fabrication and processing methods, allowing control over spatial distribution and alignment of CNTs in the matrix. For this reason, a novel process termed "matrix assisted pulsed laser evaporation" (MAPLE) was used in creating several CNT-copolypeptide nanocomposites. These results, as well as the preliminary investigation of the copolypeptide's shear piezoelectric properties, will be presented. @FootnoteText@ @footnote 1@ S. B. Sinnott and R. Andrews, Carbon nanotubes: synthesis, properties, and applications, Crit. Rev. Sol. State Mat. Sci. 26, 145, 2001.

NS-TuP12 Double-walled Carbon Nanotubes Grown on Co Tip Catalysts by Chemical Vapor Deposition, ***C.-M. Yeh***, *C.-J. Huang, M.-Y. Chen, J.C. Hwang,* National Tsing Hua University, Taiwan, R. O. C.

A cobalt tip structure has been used as the catalysts for the grown of double-walled carbon naotubes (DWCNTs) by catalytic chemical vapor deposition at 900~1000°C. The cobalt tip catalysts were fabricated by a pre-deposition of a cobalt thin layer of 0.5~10 nm on Si(100) and a sequential microwave plasma treatment at 450°C. The outer and inner tube diameters of the DWCNTs are in the range of 3~4 and 2~3 nm, respectively, determined by transmission electron microscopy. The density of DWCNTs can be enhanced by the Co tip catalysts, which structure is superior to ball-like Co islands for the growth of CNTs.

NS-TuP13 Oxide Electrolyte Nanostructures for Low Temperature SOFC Operation, ***S. Thevuthasan***, *L. Saraf, V. Shutthanandan, O.A. Marina, C.M. Wang, S. Azad, Y. Zhang, A. El-Azab,* Pacific Northwest National Laboratory

Development of electrolyte materials that possess high oxygen ion conductance at relatively low temperatures is essential to improve the performance of electrochemical devices. Ceria, doped with a divalent or trivalent cation, exhibits higher ion conductance compared with yittria-stabilized zirconia, the electrolyte currently used in solid oxide fuel cells. In this research, we have investigated layer by layer structures of highly oriented gadolinia doped ceria and zirconia in order to determine the nanoscale effects on the ion conductance. Highly oriented multilayered nanostructures of gadolinia-doped ceria and zirconia with interfaces parallel and perpendicular to the substrate surfaces were grown on sapphire substrates using molecular beam epitaxy and glancing angle sputter deposition, respectively. These structures were characterized by several bulk and surface sensitive characterization techniques. At relatively low temperatures, the oxygen ion conductance in highly oriented layered structures was found to increase with increasing number of layers in the films with interfaces parallel to the substrate surfaces. Theoretical calculations were also performed to understand the effects of space charge regions induced by the thermodynamic equilibrium and impurity segregation as well as the influence of the grain microstructures on the electric transport processes in these materials. In addition, labeled oxygen diffusion measurements were carried out by 18O(p,alpha)15N nuclear reaction analysis (NRA) and the diffusivity correlation is established with ionic transport by measuring the oxygen ionic conductivity using impedance spectroscopy. These results will be discussed along with the

results from stability tests of these layered structures at elevated temperatures.

NS-TuP14 Hydrogen Effects on the Field Emission of Carbon Nanostructures, ***P. Miraldo***, *R.A. Outlaw, X. Zhao, J.J. Wang, B.C. Holloway,* College of William & Mary

Field emission from carbon nanostructures such as carbon nanotubes (CNT), carbon nanofibers (CNF) and carbon nanosheets (CNS) is greatly influenced by the presence of hydrogen adsorbed on the surface and dissolved in the bulk. The amount and site location of the hydrogen and how it affects electron emission has, to date, not been determined. Temperature desorption spectroscopy, electron energy spectroscopy and time of flight-secondary ion mass spectrometry were employed to examine some of these characteristics. Hydrogen was desorbed from CNS via vacuum firing (T~ 1000@degree@C for 2h for full depletion) and via thermal conditioning at emission currents of greater than 500 uA for periods of 30 min to > 2h. Following conditioning of the CNS, there was a marked improvement in the repeatability, stability and magnitude of the field emission current. Field emission was observed to increase by over an order of magnitude corresponding to the complete removal of hydrogen from CNS. Turn on voltages less than 0.8 V/@micron@ and current densities greater than 2 mA/mm2 have been observed. Raman spectroscopy performed on the CNS after conditioning revealed a significant reduction in the D/G ratio. Comparisons to the reported decrease in electron emission with hydrogen removal from CNT are presented.

NS-TuP15 Fabrication of Three-Dimensional Nanostructures with a Resolution of 10 nm and Selective Attachment of Biological Molecules using Scanning Near-field Photolithography, ***R.E. Ducker***, *M. Montague, G.J. Leggett,* University of Sheffield, UK

Scanning near-field photolithography (SNP) is a new nanolithography tool in which a scanning near-field optical microscope (SNOM) coupled to a UV laser is used to pattern organic monolayers. Here we present a detailed study of the mechanism of formation of nanostructures in self-assembled monolayers (SAM) of alkanethiols adsorbed on gold surfaces. A novel mild etch solution has been developed that can be used to selectively etch gold using a SAM resist. Used in conjunction with SNP this enables the fabrication of structures in gold that are smaller than 10 nm using light with a wavelength of 244 nm. In contrast to electron beam methods, SNP may be used under ambient or even fluid conditions. SNP can also be used to create biological nanostructures via a variety of methods.

NS-TuP16 Metal Nanostructure Growth on Molecular Buffer Layers of CO@sub 2@, ***P.S. Waggoner***, *J.S. Palmer, V.N. Antonov, J.H. Weaver,* UIUC

Buffer-layer-assisted growth (BLAG) occurs when a multilayer of condensed gas acts as the surface on which impinging atoms form clusters that subsequently diffuse and coalesce during buffer desorption. We investigated Au, Cu, and Ni nanostructure formation using buffer layers of solid CO@sub 2@ and compared the results to what has been found for solid Xe buffers. The cluster densities could be controlled from ~10@super 8@ to 10@super 12@ cm@super -2@ by taking advantage of the power law dependence of density on the buffer layer thickness. For Au and Cu, the crossover from compact to ramified structures could be followed. For Ni, even small particles were ramified. The effective activation energies for diffusion of large ramified clusters on CO@sub 2@ were determined to be 0.91, 1.02, and 0.93 eV for Au, Cu, and Ni, respectively. These were significantly higher than observed on Xe, and they reflect the higher polarizability of CO@sub 2@. The diffusion pre-factors increased exponentially with the increase in diffusion barrier, demonstrating a Meyer-Neldel compensation effect. The characteristic energy of this process, 9 meV, was higher than for Xe due to the more energetic phonons of CO@sub 2@. It is comparable to the energies of buffer phonons active during buffer desorption, revealing that cluster motion on CO@sub 2@ is a many-body process fueled by coincidence of activated buffer phonons.

NS-TuP17 Synthesis of Aligned Carbon Nanotubes by CVD Using Ball-Shaped Microwave Plasma, ***Y. Oshiro***, *S. Nishino, Y. Hayashi,* Kyoto Institute of Technology, Japan

Aligned carbon nanotubes (CNTs) have been successfully synthesized by plasma-enhanced chemical vapor deposition using ball-shaped microwave plasma in a quartz bell jar. CNTs are expected to be used as field electron emitters for a display or an X-ray source, because they have the characters of high aspect ratio, small radius of tip curvature and mechanical strength, which are required for long-lived emitters with intensive electric field at their tips even at low applied voltage. Ball-shaped microwave plasma, which is generated non-contact with a quartz bell jar, has been used for aligned CNTs growth because of high purity CNT synthesis. In the plasma, CNTs are expected to grow in an environment with few impurity inclusion by the sputtering of the wall of a quartz bell jar. 10% methane diluted in hydrogen was introduced in the bell jar chamber and the pressure was kept at 2000 Pa during the growth of CNTs. Microwave power of 450W was induced for the generation of ball-shaped microwave plasma. For the growth of vertically aligned CNTs, we placed a DC cathode plate parallel to a grounded electrode , which plays a role of an end plate for microwave propagation, to apply a uniform and intensive electric field on a substrate. Iron substrates were set on the cathode plate, to which negative bias of 300V was induced. Aligned carbon fibers of 30 nm in diameter and 800 nm in length were observed by scanning electron microscopy. These carbon fibers should be CNTs formed by tip growth, because they were hollow and had cone-shaped particles at their tips, which are generally observed to be those of iron catalytic metal in the tip-growth mode of CNTs.

NS-TuP18 Arrayed Bundles of Carbon Nanotubes for High-Intensity Field Emission: Parametric Studies of Growth and Field Emission, ***M.J. Bronikowski***, *H.M. Manohara, B.D. Hunt,* Jet Propulsion Laboratory, California Institute of Technology

We have found that Carbon Nanotubes (CNT) arranged in arrays of bundles give much greater field emission current densities that either isolated CNT or dense mats of CNT, in excess of 1 Amp/cm^2 at fields of less than 4 Volts/micron. As part of ongoing efforts to fabricate high-intensity electron-beam devices based on these arrayed CNT bundles, we have studied CNT bundle growth (by Chemical Vapor Deposition, CVD) as a function of the various CVD processing parameters, and field emission intensity as a function of CNT bundle array geometric parameters such as bundle size, spacing, and CNT length and diameter. Results will be presented from these parametric studies, in which we have optimized both CNT growth and field emission of electrons from arrayed bundles of CNT.

NS-TuP19 Suspended Carbon Nanotube Electro-Mechanical Tunneling Switch for Wireless Communication, ***Y. Song***, *J. Choi,* Wayne State University

Carbon nanotube is one of the best building blocks for future nano electro-mechanical systems especially in wireless communication application. It is originated from the excellent properties of carbon nanotubes such as high mechanical strength, chemical inertness, high aspect ratio, and good thermal conductivity. We directly fabricated laterally suspended carbon nanotube tunneling switch and studied its characteristics and performance as an electro-mechanical switch. The onset of tunneling turn-on voltage of carbon nanotube switch is as low as 2.6 V. The switching behavior of carbon nanotube electro-mechanical switch was modulated by a back gate voltage and investigated by in-situ Raman spectroscopy and impedance spectroscopy.

NS-TuP20 Experimental Evidence of p-type Doping for Long Channel Carbon Nanotube Transistor, ***D. Kang***, Samsung Advanced Institute of Technology, Korea*; N. Park,* Dankook University, Korea*; B. Kim, J. Kim,* Chonbuk National University, Korea*; W. Park,* Samsung Advanced Institute of Technology, Korea

Carbon nanotubes(CNT) show dramatic changes in physical and chemical properties under different ambient conditions because of its high surface area. However, the possibility of p-type doping has been controversial for several years. While the thermoelectric power measurement obviously reported the oxygen-induced hole doping in the bundles of nanotubes, transport measurement with single short nanotube revealed that the adsorption effect lead to the work function change of the electrode, rather than the doping the nanotube body. However, in this study, we show that the doping effect would be prominent in the single nanotube transistor when the CNT is long(~5 μm). In order to decouple mixed effects from doping and metal work function change, we masked the interface (CNT/metal) and channel (CNT) region of CNT FET with conventional photoresists, respectively and measured Ids-Vg characteristics in air and vacuum. Preliminary data show that p-doping due to adsorption of ambient gas molecules could be possible and another critical factor to govern electrical properties of long channel CNT transistors. In addition, we observe that changes in Ids-Vg and Vth (threshold voltage) are associated with where it was masked.

NS-TuP21 Electrical Properties of a Silicon Nanocrystal Embedded in a SiO2 Layer, ***J.M. Son***, *J.M. Kim, S.Y. Seong,* Myongji University, Korea*; Y. Khang, B.K. Kim, K.S. Seol, E.H. Lee, J. Lee,* Samsung Advanced Institute of Technology, Korea*; Y.S. Kim, C.J. Kang,* Myongji University, Korea

Si nanocrystal (Si NC) based device is a promising candidate for the future non-volatile memory. It is advantageous in terms of low power consumption, small device size, excellent stress induced leakage current (SILC) immunity and better retention. Since the characteristics of Si NCs memories in which the conventional poly-Si floating gate is replaced by an array of Si NCs is affected by the electrical properties of each NC, the isolation of Si NCs plays an important role. The Si NC samples produced by laser ablation method were followed by sharpening oxidation steps. In these steps Si NCs are capped with a thin oxide layer of 1~2nm thickness for isolation and the size control. It also affects the interface states of NCs, resulting in the change of electrical properties. To find out this effect, we observed localized electrical properties of a capped Si NC by scanning probe microscopy (SPM). And these results were compared with C-V characteristics of the conventional MOS capacitor structure.

NS-TuP22 Synthesis of Carbon Nanofibers on TiW Substrates and Their Field Emission Properties, ***K. Hou***, *J.J. Wang, P. Miraldo, R.A. Outlaw, B.C. Holloway,* College of William and Mary

Spaghetti-like and aligned carbon nanofibers have been synthesized on TiW substrates by DC PECVD at a substrate temperature of 635°C. The morphology transition from spaghetti-like to aligned carbon nanofibers has been observed to be a function of plasma power. It is found that the growth rate plays an important role in determining the morphology of carbon nanofibers. When the growth rate is less than 150 nm/min, aligned carbon nanofibers can be fabricated. Otherwise, spaghetti-like carbon nanofibers are formed. The growth rate of carbon nanofibers fabricated on TiW substrate at 550°C is also measured in this work. The field emission properties of both spaghetti-like and aligned carbon nanofibers grown on TiW substrate at 635°C have also been investigated.

NS-TuP23 Temperature-induced Control of the Aspect Ratio of Gold Nanorods, *H.J. Park, C.S. Ah,* Korea Research Institute of Standards and Science*; K.-P. Lee,* Kyungpook National University, Korea*; I.S. Choi,* KAIST, Korea*;* ***W.S. Yun***, Korea Research Institute of Standards and Science

Aspect ratio of gold nanorods can be controlled by simply adjusting the reaction temperature in the seed-mediated synthesis of the nanorods. At various reaction temperatures between 276 and 313 K, the gold nanorods were prepared by the injection of gold nanoparticles of around 4 nm in diameter into a reaction mixture consisting of hydrogen tetrachloroaurate, hexadecyltrimethylammonium bromide, and ascorbic acid. Average aspect ratio of the resulting nanorod increases from 1 to about 40 with decreasing the reaction temperature, which can be attributed to temperature-induced change in the stability of the micellar templates.

NS-TuP24 Controlled Gold Nanowires using 2-Aminoethanthiol Capped Gold Nanoparticles on DNA Molecule as Template, ***H. Kim***, *B. Hong,* Sungkyunkwan University, Korea*; Y.-H. Roh,* Sungkyunkwan University, Korea, Republic of Korea

We developed a simple technique to form Au-nanowires (AuNWs) by the conjugation of 2-aminoethanthio-capped gold nanoparticles (AET-AuNPs) and the immobilized DNA molecules on 3-Aminopropyltriethoxysilane (APS) coated Si wafers. The AuNPs coated with AET monolayers have been electrostatically assembled along DNA molecules by careful control of the relative molar quantities of AuNPs and AET. We carried out a variety of AuNPs sizes (2, 5, 10 nm) to form the various nanowires, and the various sizes of nanowires were achieved. The gold nanowires formed in this study were confirmed by atomic force microscopy (AFM). In addition, we measured an electrical conductivity of AuNWs located between microfabricated electrodes. The investigated nanowires exhibit ohmic transport behavior at room temperature.

NS-TuP25 Synthesis and Characterization of SiC Nanowires and SiC/ZnO Hetero-Nanostructure Grown by Direct Heating Method, ***Y. Ryu***, *Y. Tak, K. Yong,* POSTECH, Korea

SiC is a suitable material for the fabrication of electronic devices operating at high power, high temperature and high frequency due to its unique physical, mechanical and electronic properties. Cubic phase SiC nanowires were synthesized in large quantity by simply heating NiO catalyzed Si substrates at the growth temperature of about 1050 @super o@C. A carbothermal reduction of WO@sub 3@/C provided reductive environment and also carbon source to synthesize crystalline SiC nanowires. SiC nanowires were 20-50 nm in diameter, and the as-grown nanowires were coated with SiO@sub 2@ sheath of ~ 20 nm thick. The grown nanowires were characterized using SEM, TEM, EDX, Raman spectroscopy, FTIR and XRD. Also, the electron field emission properties of the SiC nanowires and core-shell SiC-SiO@sub 2@ nanowires were investigated. The turn on field at the emission current density of 10 μA/cm@super 2@ was below 4 V/μm, and it showed uniform emission image. Hetero-nanostructure of ZnO nanorods(NR)/SiC nanowires(NW) were produced using a two step process: direct growth and metal-organic chemical vapor deposition (MOCVD). Atomically abrupt interface was observed at the heterojunction of ZnO NR/SiC NW. The photoluminescence (PL) of aligned ZnO nanorods will be discussed as well.

NS-TuP27 Formation of Ge Nanocrystals in Hf based High-K Dielectrics for Nonvolatile Flash Memory Device Application, *J. Chen,* National University of Singapore*; A.-Y. Du,* Institute of Microelectronics, Singapore*;* ***W.J. Yoo***, National University of Singapore, singapore*; D.S.H. Chan,* National University of Singapore

Nanocrystals (NCs) floating gate has received considerable attention for the future nonvolatile flash memory devices because its discreteness of charge storage suppresses lateral migration of charges, enhancing immunity to oxide defects compared with conventional flash memories using continuous floating gates. High-K dielectrics in place of conventional SiO@sub 2@ can further improve programming efficiency, data retention and read speed of flash memory because of lower F-N tunneling barriers and small equivalent oxide thicknesses. In this work, methods to form Ge nanocrystals embedded in main stream high-K dielectrics, HfO@sub 2@ and (HfO@sub 2@)@sub x@(Al@sub 2@O@sub 3@)@sub 1-x@ (HfAlO) were introduced and compared. Temperature dependence of phase separation process in the formation of Ge NCs in HfO@sub 2@ and HfAlO matrices was studied using X-ray photoelectron spectroscopy. Transmission electron microscopy and energy dispersive X-ray spectroscopy show that Ge NCs can form in either HfAlO or HfO@sub 2@, and the location of Ge NCs varies depending on the high-K films. It is found that, in HfAlO, Ge NCs are well sandwiched in amorphous HfAlO matrix. However, in HfO@sub 2@, Ge NCs are located in grain boundaries of polycrystalline HfO@sub 2@, and most of Ge NCs are in direct contact with Si substrate or gate electrode of memory devices because of the extrusion effect of the growth of HfO@sub 2@ crystal grains on Ge NCs. This results in a significant difference in data retention of memories employing these structures. Flash memories employing Ge NCs embedded in HfAlO can maintain a memory window of 0.5 V in 10 years, whereas flash memories employing Ge NCs embedded in HfO@sub 2@ show a memory window closing only within 2 minutes.

NS-TuP28 Electrical Characteristics of DNA-Nanoparticle Networks using Scanning Probe Microscopy, ***N.J. Lee***, *Y.J. Kim, J.S. Kim, B.H. Nahm,* Myongji University, Japan*; D. Jeon,* Seoul National University, Korea*; Y.S. Kim, C.J. Kang,* Myongji University, Korea

Transport properties of the DNA-nanoparticle networks constructed by the self-assembly of biotinylated DNAs and streptavidins are studied by scanning probe microscopy (SPM). First, we measured I-V characteristics of DNA network linked between two metal electrodes deposited on mica surface, and these results were classified with respect to the conformational change of DNA molecules. Next, SPM probe tip was used as a counter electrode for the fixed metal electrode. In this experiment, only one end of DNA molecule was attached to the fixed electrode and the tip was scanned over DNA molecules to measure the local property. We also monitored capacitance or potential difference within the networks with SPM while biasing the network. To find out the charging effect in the network, we directly injected charge into the DNA molecule through SPM tip and performed microscopy and spectroscopy. In this talk, local electrical properties of the DNA-nanoparticle networks observed by SPM and their possibility to be applied for nano devices will be presented.

NS-TuP29 Observation of Broad Strong Red Photoluminescence Band in Indium Oxy-nitride Nanoparticles, ***T.S. Ko***, *C.P. Chu, W.T. Hsu, H.C. Kuo, S.C. Wang,* National Chiao Tung University, Taiwan

Indium oxy-nitride nanoparticles were synthesized on silicon substrate in nitrogen atmosphere using a method involving thermal evaporation of pure indium. Nanoscale compositional analysis by energy dispersion spectrum showed the existence of indium oxy-nitride compound. Scanning electron microscopy investigations showed shape transformation from amorphous sphere to well-shaped octahedron with an average nanoparticle size from 180 nm to 1 μm when growth temperature of substrate increased from 700 to 900 °C. Photoluminescence study was performed on indium oxy-nitride nanoparticle samples grown at different

temperatures. It was found that all of samples grown at different temperatures exist a broad emission band centered around 690 nm with a full width at half maximum is about 250 nm, spanning the whole red region. The emission intensity increases with growth temperature, which suggests the formation of high quality indium oxy-nitride nanoparticles with increasing temperature. The photoluminescence results indicate the indium oxy-nitride nanoparticle samples have potentialities of developing into red phosphor system for lamp applications.

NS-TuP30 Single-Crystal GaN Nanorod Arrays Grown by UHV RF-MOMBE, ***C.N. Hsiao***, *C.-C. Kei,* National Applied Research Laboratories, Taiwan; *C.K. Chao,* National Central University, Taiwan; *S.-Y. Kuo,* National Applied Research Laboratories, Taiwan

Well-aligned GaN nanorod arrays have been grown by ultra-high vacuum metal organic molecular beam epitaxy using RF radical nitrogen (RF-MOMBE) on c-sapphire substrates without any catalyst. The corresponding microstructure and growth kinetics of rods were investigated by in-situ reflection high-energy electron diffraction, scanning electron microscopy, transmission electron microscopy, energy dispersive spectroscopy, x-ray diffraction, micro-Raman spectroscopy, photoluminescence and high resolution transmission electron microscopy (HRTEM). It was found that the length and diameter of nanorods varies with the growth temperatures, and the rod number density can reach around 10@super 10@ cm@super -2@. HRTEM and corresponding diffraction patterns have revealed the GaN nanorods have a dislocation free, single-crystal hexagonal wurtzite structure with preferential (0001) orientation. However, the selected area electron diffraction patterns (SADPs) for the interface were not clear enough to identify corresponding orientation relationship between rod and substrate. Further research about growth mechanism is still needed in this area. The findings in this work show that the size and density of the rods can be controlled by adjusting the III/V ratio, RF plasma power and growth temperature. In contrast to previous works, the process requires neither catalyst nor the effect of nanometer-sized confinement such as carbon nanotubes. Thus, the single-crystal and dislocation-free GaN nanorods arrays might be useful for practical applications in nanoscale optoelectronic and electronic devices.

NS-TuP31 ZnXCd1-XSe Ternary Semiconductor Nanoalloys, ***H. Lee***, *L. Hardison, H. Yang, V.D. Kleiman, P.H. Holloway,* University of Florida

ZnxCd1-xSe quantum dots have been synthesized by a high temperature colloidal method using a trioctylphosphine oxide (TOPO) solution. Oleic acid complexes of Cd and Zn were used for the metal sources in reactions that produced ZnxCd1-xSe nanoalloys. Nanoalloying was achieved during the one-step synthesis process that led to a ZnSe shell on the CdSe core. Reaction temperatures below 250oC led to less alloying and less spectral shifts as compared to dots synthesized at 320oC. Smaller nanocrystals were obtained at lower growth temperature due to a smaller critical radius of nucleation, leading to a large nucleation rate. ZnCdSe nanorods were also synthesized from CdSe/ZnSe coreshell nanorods via a solution thermal alloying process at 270~280oC. CdSe nanorods were prepared using tetradecylphosphonic acid (TDPA)/TOPO surfactants, and a ZnSe shell was grown on CdSe nanorods at 180~190oC. These nanorods were characterized as a function of alloying time using X-ray diffraction, Raman, transmission electron microscopy, and time-resolved photoluminescence spectroscopy. Femto-second transient absorption in the visible emission spectra was used to study the alloying mechanism(s). The decay of luminescence in ZnxCd1-xSe nanoalloys is best fit by stretched-exponential function and the significance of this observation will be discussed.

NS-TuP32 The Dependence of Photoluminescence Characteristics of In2O3 Nanowires on the Zn Doping Level, ***C.L. Hsin***, *J.H. He, L.J. Chen,* National Tsing Hua University, Taiwan, R.O.C.

Nano-scaled materials have attracted increasing attention because of their novelty and potential applications. In this paper, we report the growth of In2O3 nanowires with different zinc doping levels in the vacuum furnace by a vapor transport and condensation method. The photoluminescence properties were measured and discussed Self-assembled indium oxide nanowires with different zinc doping levels have been synthesized on the silicon wafer in a vacuum furnace. The morphologies, structures and chemical compositions have been studied by field emission scanning electron microscopy and transmission electron microscopy. The photoluminescence properties of the samples were measured at room temperature. The presence of metal particle at the top indicates that the growth of the nanowire is by VLS mechanism. The intensity variation with the doping level of the samples can be seen clearly. The band diagram can explain the photoluminescence characteristics. The photoluminescence properties are attributed to the radiative recombination between oxygen vacancies, zinc impurities and indium-oxygen vacancy pairs.

NS-TuP33 Synthesis of One-dimensional Well-aligned ZnO Nanorods on Patterned Structures, ***C.W. Wang***, *J.H. He,* National Tsing Hua University, Taiwan, ROC; *L.J. Chen,* National Tsing Hua University, Taiwan, ROC., Taiwan, R.O.C.; *G.C. Wu, C.T. Chia,* National Taiwan Normal University, Taiwan, ROC

The synthesis of one-dimensional (1D) semiconducting oxide nanomaterials has drawn a great deal of attention. ZnO has a wurtize structure with applications in catalysts, sensors, actuators and transducers. Under controlled conditions, 1D well-aligned ZnO nanorods are synthesized by a simple vapor transport via vapor-liquid-solid (VLS) process on patterned single crystal (11-20) sapphire. The patterning methods include atomic force microscope-tip induced technique and nanosphere lithography. From FESEM images, ZnO nanorods are vertically aligned on the substrate and have uniform diameter of about 100 nm. From TEM images, ZnO nanorods are single crystal and grown along c-axis. Photoluminescence measurements show that a peak occurs at 380 nm which is attributed to band edge emission.

NS-TuP34 Amorphous Nanotubes by Self-Assembly of Amphiphilic Bi(hexadecylamine) Zinc Sulfato Complex with Size Tunability, ***G.W. Huang***, *J.H. Wang, H.C. Chen,* National Tsing Hua University, Taiwan, Republic of China; *L.J. Chen,* National Tsing Hua University, Taiwan, Republic of China, Taiwan, R.O.C.

We describe on the formation of amorphous (C@sub 16@H@sub 33@NH@sub 2@)@sub 2@ZnSO@sub 4@ nanotubes based on directional buttom-up self-assembly process. Through catalytic chemical reaction, the bi-hexadecylamine coordinated zinc sulfato complex is generated as a long-period molecular chain. The nanotubes were analyzed by FTIR, ESCA and line-scan EDX analysis to confirm the nanotubes are composed of (C@sub 16@H@sub 33@NH@sub 2@)@sub 2@ZnSO@sub 4@ complex. The zinc coordinated bi-hexadecylamine provides a multiple intermolecular hydrophobic interaction and drives these molecular backbones to be close together. The as-bulit nanotubes were identified through analytical electron microscope observations, which reveal the nanotubes possess outer diameters of 60-90 nm and on inner diameter of 20 nm with length up to several micrometers. Additionally, through stoichiometry adjustment the length could be reduced drastically to hundreds of nanometer. The tunability in length is also reflected from photophysicical properties with size-dependent optical characteristics. Further molecular packing profile revealed by small angle X-ray scattering strongly suggests and sustains the long range ordering (ca. 3.99 nm d-spacing) within these nanotubes.

NS-TuP35 Formation of Ordered Nanodots with Si-Ge Superlattices by One Step Etching Process, ***H.C. Chen***, *S.W. Lee,* National Tsing Hua University, Taiwan, Republic of China; *L.J. Chen,* National Tsing Hua University, Taiwan, Republic of China, Taiwan, R.O.C.

Semiconductor superlattices are attracting increasing attention due to their potential applications in thermoelectric and optoelectronic devices. While the 2-dimensional (2D) semiconductor possesses promising properties for optoelectronic devices such as light emitting diode, heterostructure formation in zero-dimension (0D) nanostructure may provide even more attractive characteristics and improve device performance. By the use of comparably low etching-rate and size uniformity of Ge QDs, a method was developed to fabricate nanodots with excellent uniformity over large area, containing Si-Ge superlattices structure. The density of the nanodots is about 1*10@super 10@ /cm@super 2@, equivalent to that of original Ge QDs. Pyramid-like nanodots containing Si-Ge superlattices with 35 nm in height and 80 nm in diameter have been successfully fabricated. The use of Ge QDs/Si-Ge superlattices heterostructure takes advantages of not only Ge QDs with good size uniformity and low etching-rate to obtain nanodots with Si-Ge superlattices structure, but also compatible with the Si/SiGe-based integration technology.

NS-TuP36 Synthesis of Au Nanotubes with SiO@sub x@ Nanowires as Sacrificial Templates, ***M.Y. Lu***, *Y.C. Chang,* National Tsing Hua University, Taiwan, ROC; *L.J. Chen,* National Tsing Hua University, Taiwan, ROC, Taiwan, R.O.C.

Gold nanotubes with SiO@sub x@ nanowires as sacrificial templates have been synthesized. SiO@sub x@ nanowires were functionalized by 3-aminopropyl trimethoxysilane (APTMS) that generates a charged surface. The attachment of negatively charged gold nanoparticles was followed. The coverage of Au nanoparticles was initially less than 30 percents. Further coverage was achieved by the reduction of gold hydroxide to grow the

continuous nanoshell on Au nanoparticles, which serve as nucleation sites. The final coverage of gold nanoshells on SiO@sub x@ nanowires depends strongly on the relative amount of SiO@sub x@ nanowires in gold hydroxide solution. TEM images showing the progressive growth of gold shells on SiO@sub x@ nanowires decorated with Au nanoparticles. FESEM image shows the open ends of Au nanostructures after etching by HF solution confirming the formation of Au nanotubes by a simple route.

NS-TuP37 Orientation Controlled Growth of Epitaxial SiNWs Networks in Ar Ambient, ***H.W. Wu***, *H.C. Chen,* National Tsing Hua University, Taiwan, ROC*; L.J. Chen,* National Tsing Hua University, Taiwan, ROC, Taiwan, R.O.C.*; C.J. Tsai,* National Tsing Hua University, Taiwan, ROC

Epitaxial silicon nanowire networks have been synthesized with a convenient annealing process in Ar ambient. Au nanoparticles were used as catalysts for nanowire synthesis via the vapor-liquid-solid growth mechanism. From the SEM observation, silicon nanowires form rectangular networks on (100) Si, and parallel straight lines on (111) Si. The diameters of silicon nanowires are between 10 and 60 nm. Structural characterization showed that the silicon nanowires grow primarily along the directions. The heights of silicon nanowires are between 3 and 20 nm. For applications in nanotechnology, growing silicon nanowires epitaxially on a suitable substrate promises to realize a high density of integrated devices based on nanowires.

NS-TuP38 QCM Studies of the Slippage of Solid and Liquid Krypton Monolayers on Metal(111) and C60 Surfaces, ***T. Coffey***, *J. Krim,* North Carolina State University

We report a Quartz Crystal Microbalance (QCM) study of the nanotribology of solid and liquid krypton monolayers adsorbed on Cu(111), Ag(111), Ni(111), and C60 substrates at 77.4 K. We document the liquid-solid phase transition and compare the slip times of the krypton for the various substrates. The slip times for the solid krypton monolayers are longer than the slip times for liquid krypton monolayers on metal substrates and monolayer C60 films, as observed previously for krypton/Au(111). However, for bilayer C60 films, the jump in slip time at the liquid-solid phase transition is not present. We discuss these topics and the underlying reasons.

NS-TuP39 Nanotribological Effects of Silicone Type and Deposition Level and Surfactant Type on Human Hair using Atomic Force Microscopy, ***C.A. LaTorre***, *B. Bhushan,* The Ohio State University

The atomic/friction force microscope (AFM/FFM) has recently become an important tool for studying the micro/nanoscale structure and tribological properties of human hair. Of particular interest to hair and beauty care science is how common hair care materials, such as conditioner, deposit onto and change hair tribological properties, since these properties are closely tied to product performance. Since conditioner is a complex network of many different ingredients (including silicones for lubrication and cationic surfactants for static control and gel network formulation), studying the effects of these individual components can give insight into the significance each has on hair properties. In this study, AFM/FFM is used to conduct nanotribological studies of surface roughness, friction force, and adhesive force as a function of silicone type, silicone deposition level, and cationic surfactant type. Changes in coefficient of friction as a result of soaking hair in de-ionized water are also discussed.

NS-TuP40 Morphological, Nanomechanical and Cellular Structural Characterization of Human Hair and Conditioner Distribution Using Torsional Resonance Mode with an AFM, *B. Bhushan,* ***N. Chen,*** The Ohio State University

Characterization of cellular structure and chemical and physical properties of hair are essential to develop better cosmetic products and advance the biological and cosmetic science. Although the morphology of the fine cellular structure of human hair has traditionally been investigated using scanning electron microscopy (SEM) and transmission electron microscopy (TEM), atomic force microscopy (AFM) can be used for characterization in ambient conditions without requiring specific sample preparations and surface treatment. In this study, tapping mode (TM) and torsional resonance (TR) mode in an AFM are compared for measurements of stiffness and viscoelastic properties mapping of the materials using amplitude and phase angle imaging. The TR mode shows advantages in resolving in-plane (lateral) heterogeneity of materials. The TR mode has been used for investigating and characterizing fine cellular structure of human hair. Various cellular structure (such as the cortex and the cuticle) of human hair and fine sublamellar structures of the cuticle, such as the A-layer, the exocuticle, the endocuticle, and the cell membrane complex could be easily identified. The distribution and thickness of conditioner on treated hair surface affects tribological properties of hair. The conditioner thickness has been estimated using force distance measurements with an AFM.

NS-TuP41 Atomic-scale Studies of Friction and Nano-Indentation, ***T. Filleter***, *S. Maier, R. Bennewitz,* McGill University, Canada*; E. Meyer,* University of Basel, Switzerland

The development of Scanning Force Microscopy has provided us with tools to study friction and wear on the nanometer scale. The characteristic atomic stick-slip instability in friction force measurements is caused by the jump of the contacting tip from one atomic position to the next. Thermal fluctuations in the combined system of tip, surface, and force sensor play an important role for the development of the stick-slip behavior. We measured the friction force for atomic stick-slip friction of a nanometer-sized tip sliding on a KBr (100) surface in ultra-high vacuum. Our friction force microscope allows us to detect force fluctuations up to 3 MHz, well above the mechanical resonance of the force sensor. We could track thermal fluctuations and found that the duration of the slip event shows a broad distribution even for slips over neighboring atomic positions. The indentation of surfaces by sharp tips is a standard method used to determine hardness and elastic modulus of materials. Scaling these experiments to small lengths can probe the initial stages of permanent deformation. Atomic scale plastic deformation at crystal surfaces has been achieved and characterized by use of non-contact force microscopy in ultra-high vacuum. A sharp silicon tip, first implemented as a nano-indenter, was used to image the atomic structure of displaced material on Cu (100) and KBr (100) surfaces. Under nano-Newton loading conditions the debris reorganizes in crystalline terraces with the same orientation as the underlying crystal.

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