SYMPOSIUM Y
Nanopatterning: From Ultralarge-Scale Integration to Biotechnology

November 25 – 29, 2001

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*Invited paper
TUTORIAL

FTY: NANOFAbrication for Cellular Engineering
Sunday, November 25, 2001
200 p.m. - 5:00 p.m.
Room 204 (Hynes)

This tutorial will address key issues of nanofabrication for biocompatible substrates. A review of the nanofabrication techniques suitable for patterning biocompatible materials will be given. The emphasis will be put on the effect of controlled surface topography on cell adhesion, growth and motility. Applications including in vitro engineered tissue and bone cells optimally grown on bioadhesive templates will be described. A brief introduction to emerging biochips will then be given.

Instructors:
Malik Richele, Centre for Cell Engineering, Univ of Glasgow (UK)
Mehemet Toner, Harvard Medical School, Massachusetts General Hospital

SESSION Y1: ADVANCED MATERIALS AND PROCESSES FOR NANOLITHOGRAPHY
Chairs: Kenneth E. Gonsalves and Tadh Marhari
Monday Morning, November 26, 2001
Back Bay D (Sheraton)

8:30 AM #Y1.1
RESIST REQUIREMENTS FOR ELECTRON PROJECTION AND DIRECT WRITE NANOLITHOGRAPHY

Aspects of resist properties required for nanolithography using high-energy electrons are described in this paper. High-energy electron lithography, such as Electron Project Ion Lithography (EPL) or Direct Write e-beam lithography (DWL), does not have the absorption limitations encountered in DUV lithography and other optical lithography alternatives. With no opacity limitations, concentration levels and types of photo-acid generators (PAGs) can be added with more flexibility. These resist designs are more resistant to high-energy electrons, as long as development interactions and imaging quality are not compromised. This paper describes a series of experiments where by extrapolating from DUV and EUV resist concepts optimized e-beam sensitive resists can be obtained. This study shows that, as for DUV resists, intercomponent interactions between PAG, base and polymer resists are crucial for image formation. Optimization of the resist processes requires a detailed understanding of the image formation process during exposure. This process has been simulated using discrete models from exposure through development for a positive EPL or DW resist. Results of the simulation have aided in a better understanding on the differences in imaging characteristics of e-beam resists and DUV or other optical resists. For example, the exposure process for 45 nm contact hole arrays was simulated and compared to experimental results obtained using a 100 Kve JOEL JBX-500FS/5 DW tool, showing excellent agreement. The simulation tool provided detailed information on ionization statistics and photoacid generation due to exposure to high-energy electrons. Ionization statistics show that most of the secondaries generated in the resist have energies well below 100 eV, peaking at around 10 eV. At these low energies impact ionization or plasmon generation are not possible, which means other types of interactions between secondary electrons and PAG come into play for photo-acid generation.

9:00 AM #Y1.2
FULLERENE NANOComposite RESIST FOR 100-KV ELECTRON-BEAM NANO-PATTERNING
Tetsuya Ishii, NTT Photonics Labs, Atsugi, Kanagawa, JAPAN; Yuka Mura, Tokyo Univ of Agriculture and Technology, Dept of Applied Chemistry, Tokyo, JAPAN; Kiyotaka Shigehara, Tokyo Univ of Agriculture and Technology, Dept of Applied Chemistry, Tokyo, JAPAN

Electron-beam lithography (EBL) is widely employed for the research and development of next-generation LSIs and novel innovative devices. In order to improve the resolution in EBL, it is essential to apply a thinner resist film to minimize the scattering effects of electrons. We have developed a novel resist composition that incorporates fullerene molecules [C60, C70] into a positive-tone electron beam resist, ZEP520 and demonstrated a resolution improvement by using an ultrathin film that is made possible by enhanced etching resistance. In addition to resist thinning, the general trend has been to use a higher acceleration voltage for increased beam resolution as well as decreased scattering effects. Several exposure tools with an acceleration voltage of 100 kV are currently available on a practical basis. The combination of fullerene nanocomposite resist and a 100 kV tool has the potential to further improve the resolution and will extend EBL versatility in nanolithography. In this paper exposure characteristics of nanocomposite ZEP are examined for various nanodevice fabrications. Employing the unique characteristics of fullerene nanocomposite resist, i.e., that sensitivity can be readily changed with fullerene content due to the dissolution inhibiting effect of fullerene, we constructed a bilayer resist system for lift-off comprising a fullerene-incorporated ZEP top layer and a pure ZEP bottom layer. Some examples of densely packed nanodot patterns fabricated by the bilayer system exposed with a 100 kV tool will be presented. Fullerene-derivative nanocomposite systems have shown better sensitivity characteristics due to the enhanced solubility of the derivatives. The sensitivity of the systems can be significantly improved by using a multi-functional fullerene as an additive. Some advanced fullerene nanocomposite systems will be discussed.

9:30 AM #Y1.3
CHEMICALLY AMPLIFIED RESIST APPROACHES FOR E-BEAM LITHOGRAPHY MASK FABRICATION
J.B. Malandro, Z. Tan, Etec Systems, Inc., and Applied Materials company, Hayward, CA; M. Andopoulous, IBM T.J. Watson Research Center, Yorktown Heights, NY; R. Brainerd, Shipley, Marlborough, MA

This paper describes several e-beam resists systems utilizing chemical amplification suitable for mask fabrication for device generations below 100 nm. The challenges of mask fabrication for future device generations will be presented together with the stringent resist requirements. In particular, three resist systems developed specifically for mask fabrication will be described: a Si Lopez version of the IBM KRS-XE resist (now commercially available) developed at IBM Research; a modified ESCAP resist with enhanced properties developed at Shipley and a new MANA resist also developed at Shipley. Chemically amplified resists for mask making on glass require better PEB latitude than resists utilized for device fabrication on wafers. This is due to the different thermal properties of the resist substrate. Relatively thick glass plates are very difficult to heat uniformly, and thermal time constants play a much larger roll in the resist development characteristics compared to high thermal conductivity silicon wafers. The etching properties, PEB latitude, shelf life stability and outgassing properties of the newly developed resist systems will be presented and compared with common resists. Some of the resist properties are summarized in the table below. Resist Parameter [H] KRS-XE [New] Shipley 9947A [New] MANA [New] Sensitivity (µC/cm) 600 Kve 3.5 8.2 1.7 Resolution (nm) 100 60-80 (dense and so) 100±50 Aspect Ratio ≥3:1 3.9 Dry etch resistance ≥1 nm/sec-20%. Better than Novolak Experiments in progress in progress Contract >10 10.1 >10.1 Exposure Latitude >30% >2% TBD PEB Sensitivity nm/FCE TBD TBD Commercialization Very likely after KRS-XE becomes available TBD This is the first time this kind of resist was developed. An important topic to discuss is the difficulty of commercializing a new e-beam resist suitable for mask fabrication. This is mainly due to the relatively small volumes required when compared to resists suitable for optical lithography device making. This paper was partially supported by a DARPA/SPAWAR contract with Etec Systems [an Applied Materials Company]. IBM Corporation and Shipley were subcontractors to Etec Systems under DARPA/SPAWAR contract No. N66001-91-C-8485.

10:30 AM #Y1.4
THE ROLE OF FLUOROPOLYMERS IN NEXT GENERATION LITHOGRAPHY
Christopher K. Ober, Young Bae, Dirk Schmidjohann, Victor Pham, Gann Wehbe, Cornell University, Dept of Materials Science & Engineering, Ithaca, NY; William Conley, International Sematech, Austin, TX; Karen Gleeson, Hilton Pryce-Lewis, MIT, Dept of Chemical Engineering, Cambridge, MA

Fluoropolymers, materials long ignored as photoresists, have recently become very interesting as possible lithographic materials because of their unusual transparency and low dielectric constant properties. This presentation will first overview our recent efforts in the design and synthesis of 157 nm resists. Reverse soluble polymers containing perfluorocarbon containing polymers have been shown to have transparency as 157 nm and can be patterned using chemically amplified resist strategies to sub-100 nm dimensions. The properties of these and related aqueous base soluble polymers and their syntheses will be described. If the fluorine density is increased, an extremely non-polar, insulating material can be produced. As the second part of this presentation, CVD deposited fluoropolymers and their development using high density CO2 will be described. Images as small as 30 nm have been produced using this technique. The enabling features and the environmental aspects of this work will be described. The authors wish to thank the Semiconductor Research Corporation, the National Science Foundation, Intel and International Sematech for financial support.
11:00 AM *Y1.5
CONFINEMENT EFFECTS ON ACID TRANSPORT IN ULTRATHIN CHEMICALLY AMPLIFIED PHOTORESISTS.
Daric L. Goldfarb, Marie Angelopoulos, and HMT J. Watson Research Center, Advanced Lithography Materials and Processes, Yorktown Heights, NY; Brian Frinque, Sean D. Burns, C. Grant Willson, Univ. of Texas, Dept. of Chemistry and Chemical Engineering, Austin, TX; Eric K. Liu, Ronald L. Edsall, Christopher L. Schwartz, and Wen-B. Wu, National Institute of Standards and Technology, Polymers Division, Gaithersburg, MD.

In the next few years, the resolution limits for the deep UV photolithographic processes widely used in the microelectronics industry must be extended to sub-100 nm length scales to keep pace with the persistent demand toressive increasingly smaller device features. However, both sub-100 nm lithography and device patterning are being limited by a number of fundamental resist limitations that have yet to be addressed adequately. For example, device dimensions below 100 nm will require critical dimension controls of 10 nm or better, approximately the same size of the macromolecules used in photolithography, and it is unclear whether such a fine level of control can be achieved. Furthermore, the optical solutions for sub-100 nm lithography, including 157 nm excimer lasers and EUV lithography sources, are strongly absorbed by most polymer films. At these wavelengths the overall film thickness needs to be 100 nm or less for uniform illumination throughout the film thickness. Under these conditions the polymers are highly confined by the two-dimensional plane and have the characteristics of thin film geometry and deviations in material properties, such as the glass transition temperature, viscosity, transport parameters, etc., which are likely. In this work, bilayers of isotropically labeled protected and unprotected chemically amplified photoresists are used to create a two-dimensional model of the line edge in a lithographic feature. X-ray and neutron reflectivity are used to quantify the spatial and temporal (kinetics) characteristics of the photogenerated acid diffusion and the resulting depletion at the buried interface as a function of film thickness and the baking temperature. The spatial extent of reaction in the buried interface is then correlated with the resulting roughness and the change in film thickness that occur upon developing the exposed film, indicative of the critical dimension control achievable in highly confined photoresist films.

SESSION Y2: ADVANCED MATERIALS AND PROCESSES FOR NANO LITHOGRAPHY

130 PM *Y2.1
PREDICTING IMAGE PLACEMENT DISTORTIONS INDUCED DURING NAPATTERNING. Roxten L. Englesland, Edward G. Lovell, Phillip L. Reu, Computational Mechanics Center, University of Wisconsin, Madison, WI.

Advanced lithographic technologies face a difficult challenge in order to meet the stringent overlay requirements for sub-100 nm lithography. Extending the lithography technology to the 70 nm node will require an innovative approach to the lithography process. This paper presents a preliminary investigation of the effects of the mask design on the overlay error. These techniques are used to simulate the development of advanced lithographic masks for the sub-100 nm regime. Finite element (FE) modeling and simulation is being used to investigate the effects of mask design, fabrication processes, and system parameters on the performance of the overlay error. This paper presents the results of a comparison study of continuous membrane versus stencil mask formats for the fabrication of Electron-beam Projection Lithography (EPL) masks. To illustrate the influence of these parameters, a pattern design was employed: (a) an interconnect layer from an SRAM design, which is a repeating orthorhombic-like layout, and (b) a dense pattern, which simulates the contact layer of the same design. Equivalent modeling techniques were used to simulate the effects of mask design and fabrication parameters. This work demonstrated that the mask design has a significant impact on the overlay error and that the mask design can be optimized to minimize the overlay error.
metallic compound presence and their unconventional processing demands discouraged their further use in microolithography. In this paper routes to the capability of using these compounds in co-bombed nanolithography and possibly in mask fabrication are evaluated. Different resist formulations, where poly (vinyl alcohol) and poly (methyl methacrylate) are used as base polymers will be discussed along with the related process issues. First results from the use of polyoxometallate compounds as active elements, or components, of molecular electronic nanodevices will be also presented. The main reason for selecting molecules of this class is their well-defined and stable structure lifetimes in the laughing wavelength range of 248nm. To further demonstrate the polyoxometallate compounds as active elements, the following molecular electronic nanodevices will be presented. The reduction-oxidation, and catalytic properties. Due to their structural resemblance to semiconductor materials these compounds can be considered as zero dimension semiconductors. The electronic transport properties of the composite materials have been tested using planar devices with contact distances of 40nm, 50nm and 250nm. Contacts were fabricated using electron beam lithography and a lift-off process. Even at room temperature conditions conductivity peaks appear in the case of distances smaller than 25nm. The position of these peaks is related to the energy distance of the HOMO-LUMO levels of the active molecules and the work function of the electrode used. The position and the size of the peaks depends upon the mean distance of the molecules as well as the electrode distance. On the other hand when the contact is illuminated, conductivity increases even by two orders of magnitude. This is attributed to the photon excitation of electrons from the HOMO.

4:15 PM #Y3.2 NOVEL APPROACHES TO NANO PATTERNING FROM SURFACE MULTIPLE LAYER INITIATED INITIATION TO HYBRID ORGANOMETALLIC ORGANIC BILAYERS.
Clifford L. Henderson, Sean Barstow, Augustin Jeykumar, Kendra McCoy, Dennis W. Hess, Georgia Institute of Technology, School of Chemical Engineering, Atlanta, GA;minor M. Tobe, Georgia Institute of Technology, School of Chemistry and Biochemistry, Atlanta, GA.

The extendibility of conventional subtractive lithographic processing using spin-coated polymeric resists faces many challenges as feature sizes in microelectronics push below 100 nm. In addition, the opacity of polymeric materials to further exposure sources presents new challenges as the radiation penetration depth decreases (e.g. 157nm, EUV, low keV e-beam). One solution to these problems is the use of so-called top surface imaging (TSI) methods in which exposure in only a thin surface layer is used to create a pattern in a much thicker bottom layer. To date, only a few thermal and soft X-ray methods have involved the use of shadowing, which have seen limited industrial use due to a variety of associated problems. This presentation will focus on our work to explore the concept of TSI using novel imaging material systems and strategies. First, results of our work on surface monolayer initiated polymerization (SMIP) will be discussed. The basic idea in SMIP is to extend the idea of TSI near its limits, i.e. where the initial image or pattern is defined in a monolayer. In this method (1) a pattern is defined by radiation exposure of a reactive monolayer whereby exposure deactivates selected areas of the monolayer, and (2) subsequently the remaining areas can be activated to generate radic (or other initiator sites) that are used to amplify the initial pattern by growth of additional polymer. This method is extremely flexible and also shows significant promise in the fabrication of sensors and biological devices. Second, we have been exploring the use of novel bilayer imaging system based on a combination of surface and photochemical TSI mechanisms. This method involved the use of a novel cromogenorganic imaging layer, Exposure of the cromogenorganic layer to radiation locally converts the film to an etch resistant metal oxide while the unconverted film can be developed away.

SESSION Y3: NEXT-GENERATION AND FLATFIELD LITHOGRAPHIES
Chair: Daniel J. C. Herr and Llado Merhlen Tuesday Morning, November 27, 2001
Back Bay D (Sheraton)

8:30 AM #Y3.3 EXTENSIBILITY OF PROXIMITY XRL: ROADMAP FOR 35 NM AND BEYOND
F. Cerrina, Electrical and Computer Engineering Center for Nanotechnology, University of Wisconsin, Madison, WI.

Proximity X-ray Lithography has a long development history, but it never quite made it in the mainstream of semiconductor lithography. It is possible that this is because the goni was set for unrealistically close targets — always the “next node”. If we ask the question “how small can we pattern using XRL?” and disconnect ourselves from the beaten paths of the SIA Roadmap, several interesting possibilities for nonproximity became possible. Hence, we will review aggressive mask design and exposure optimization for general nanopatterning at 35nm and below, showing that (based on rigorous physics-based analysis) it is possible to extend XRL to the next node of lithography regime.

10:30 AM #Y3.4 RESISTLESS PATTERNING OF MAGNETIC STORAGE MEDIA USING AN ION BEAM PROJECTION TECHNIQUE

The rapid increase of areal storage densities in magnetic hard disk drives may in the future be limited by the thermal instability of small magnetic domains which is known as superparamagnetism. A permalloy storage medium for an independent single magnetic domain bit cells would allow to further postpone this limitation. Ion
beam projection (IBP) techniques facilitate a reliable and simple process which is attractive for manufacturing of future magnetic storage devices. The complex pattern including data and servo information can be transferred into the magnetic media. Such specific structures can be already defined in a stencil mask which allows mass replication. One advantage of the IBP technique is that the complex pattern in the stencil mask can be transferred into the magnetic medium at a given demagnification factor (e.g. 8 x), which simplifies the stencil mask process. Stencil mask patterns may have either rotational or translational symmetry. Experiments are presented where Co/Pt multilayers with different aspect ratio and micro-patterns are magnetically altered in areas of local ion beam interaction. Hereby the topography of the media is preserved in contrast to other patterned media approaches. We report the influence of different ion species and ion doses on magnetic parameters of irradiated samples. Simulations of different ion doses and energies show the intermixing of Co and Pt layers in the sample and allow to predict magnetic coercivity changes in dependence of the ion doses. The later value determines the manufacturing process. An IBP tool which is currently developed within an European consortium (MEDEA) for next generation lithography will be used to evaluate a manufacturing process for magnetic storage media. This tool allows to irradiate samples up to a diameter of 17 mm with a single exposure.

11:00 AM Y3.5
LITHOGRAPHIC PERFORMANCE OF ION PROJECTION
Wilhelm H. Bruegger, FRAunhofer Institute for Silicon Technology, IST, Iffezheim, GERMANY.

As part of the European MEDEA project on Ion Projection Lithography (IPL), performed by Infineon Technologies, a process development tool has been assembled at IMS, Vienna. Recent results of the exposure tests which are now being conducted will be presented. Parallel work continues at the experimental ion projector of the Fraunhofer Institute IST. New open stencil masks produced by IMS-Chips, Stuttgart, with smaller feature sizes and aspect ratios up to 6 have been irradiated with light (He+) and heavy (Ar+) ions for the radiation sensitivity. The aim is improved etch resistivity and stability against patterning of high aspect ratio features. The high resist sensitivity below 1 micro C/cm² for 75 keV He ions and the absence of a proximity effect make ion projection a promising candidate for Next Generation Lithography.

11:30 AM Y3.6
PLASMON PRINTING: A NEW APPROACH TO NEAR FIELD LITHOGRAPHY
Pieter G. Kik, Stefan A. Maier, and Harry A. Atwater, California Inst of Tech, Dept of Applied Physics, Pasadena, CA

The minimum feature size that can be obtained using projection lithography is limited by the diffraction limit. We propose a new approach to lithography that can enable the printing of sub-wavelength patterns. The proposed method relies on the plasmon resonance occurring in nanoscale metal particles. Gold nanoparticles exhibit a collective electron oscillation (surface plasmon) when illuminated with visible light. In air this plasmon excitation occurs resonantly at a wavelength of ~400 nm, producing a strongly enhanced electromagnetic field near the particle. We propose to use this enhanced near field to locally expose a thin layer of resist. This method could enable the generation of sub-wavelength replicas of nanoparticle arrays in a parallel process, using broad beam illumination with visible light.

The applicability of the proposed scheme depends on the magnitude of the field enhancement and the exact time-dependent field distribution around the metal nanoparticles. Finite difference time domain (FDTD) simulations on 50 nm diameter gold particles in contact with a 100 nm thick layer of photoresist reveal a clear intensity enhancement in the resist just below the particle under illumination at a wavelength of ~600 nm. The lateral extent of the area where the enhanced intensity is 25 nm (less than 5% of the wavelength), illustrating the potential for producing high-resolution patterns. The maximum intensity enhancement occurs at a depth of 16 nm below the particle, and amounts to a factor 1.5. Optimum illumination wavelengths for a number of metals as well as constraints on resist thickness and substrate composition will be discussed, along with experimental results obtained using an Ar laser and commercially available photoresist.

11:45 AM Y3.7
OPTICAL NANOLITHOGRAPHY ON AZO-HYBRID GELS, THE NEAR-FIELD APPROACH
Nathalie Landraud, Frederic Chaput, Jacques Prevot, Khaled Labib, Georges Legrand, Vianchanel Salome, LPJM, CNRS-Ecole Polytechnique, FRANCE

Scanning near-field optical microscopy has been developed to capture the sub-diffraction limited resolution. Combined with the potentials of scanned probe microscopy, one of the most attractive application has been developed in our laboratory is the local modification of the physical properties of materials. We report here of the nanofabrication and characterization of topographic nanometer features on anodized functionalized solgel thin film. A combined scanning near-field optical microscope and shear-force microscopy has been utilized to observe the modification processes. Using tapered silicon nitride cantilevers, we can address a region whose size depends on the aperture at the tip of the probe as well as the tip film surface separation. After irradiation (508nm), shear-force imaging reveals protrusions with lateral dimensions as small as 50nm. Photolithography on the nanometer scale and high density optical data storage are promising applications of these experiments.

SESSION Y4: NANOFABRICATION WITH CHARGED PARTICLE BEAMS
Chair: Marie-Isabelle Banaron and Daniel J. C. Herr
Tuesday Afternoon, November 27, 2001
Back Bay D (Shearron)

1:45 PM Y4.1
FOCUSION BEAM FABRICATION OF PHOTONIC NANOSTRUCTURES. AJ. Seck, R. Chi, B. Lee, L. Chuy, J. Cheng, and P. Beyette, University of Cincinnati, Nanoelectronics Lab, Cincinnati, OH

Focused ion beam systems provide a unique device fabrication capability by being able to customize the process on a scale comparable to the ion beam parameter (<100 nm). This is particularly important for the integration of photonic devices where the presence of a large variety of materials and 3D structures make conventional planar batch processing difficult. In this paper we review several photonic devices and applications implemented with FIB nanofabrication: optical memory storage, optical waveguides, diffraction gratings. For example, high density optical memory devices have been fabricated by two bit writing approaches: FIB evaporation into GaN and GaP FIB milling of SiO2/Si. In the former approach, the memory "read" process is based on wavelength emission from Er ions. Ranging of the pattern is performed with near-infrared lasers (at 840 or 1000 nm) resulting in visible green emission (at 522 and 546 nm). 3D memory devices have shown a storage density of 1018 bits/cm2, while extension of this approach to 3D could produce very high densities (~ 1020 bits/cm3). In the latter approach, we utilize FIB milled regions of varying thickness to adjust the spectral characteristics of reflected light from a broad band source. This digital thin-film (DTF) color optical memory has been implemented in structures with 4 physical levels of 4 bits/pixels providing an equivalent storage density of ~ 1017 bits/cm2, with potential extension to ~ 1020 bits/cm3. We will also review the implementation of novel rare-earth (Er, Pr) sources required for the fabrication of certain memory and light emitting devices, the use of gas assisted (XeF2, I2) used to enhance the FIB milling process for waveguide fabrication and provide some speculation on future directions of FIB fabrication of photonic nanostuctures.

2:15 PM Y4.2
ION BEAM SCULPTING ON THE NANOSCALE. Derek Stein, Jinli Li, Michael J. Aziz, Division of Engineering and Applied Science, Harvard University, Cambridge, MA; Daniel Branton, Department of Molecular and Cellar Biology, Harvard University, Cambridge, MA; J.A. Golubenko, DEAS and Department of Physics, Harvard University, Cambridge, MA

We report on the ability to controllably transform materials on the single nanometer length scale using low energy ion beams. In addition to removing material from the surface by a sputtering process, low energy ion beam exposure stimulates significant surface atomic transport. These processes can be utilized to fabricate solid state devices and structures with single digit nanometer control in a variety of geometries and materials using a feedback controlled ion beam sculpting apparatus. Our experiments focus on ion beam sculpting nmonopoles in thin insulating membranes and reveal the dynamical nanoscale atomic transport phenomena in a quantitative manner. The results are consistent with an "atomistic" surface diffusion model and they yield parameters needed to apply the method to nanoscale device fabrication. As an application we demonstrate an electronic solid state single molecule detector, fabricated by ion beam sculpting, that operates in a gaseous environment.

2:30 PM Y4.3
NANOSCALE ELECTROCHEMICAL DEPOSITION OF METALS

Focused Ion Beams (FIB) have been widely used as a tool for TEM sample preparation and as an ion etching technique. Also, direct deposition/placement of material onto Si surfaces has been performed. While FIB offers an essential spatial resolution for these applications, its widespread use has been hindered by the comparatively long exposure times needed for submicron milling/implantation to occur. This work reports the use of FIB to produce local damage sites on the surface of p-Si that lead to the modification of the semiconductor/electrode interface behavior.

FIB: Electron Microscopy (FE-STEM) is providing nm level characterization of materials, device, and electrical properties. Examples of FE-STEM electron beam induced current (EBIC) combined with Z-contrast imaging for FIB studies and SIMS analysis used to characterize nm scale quantum well devices will be presented.

4:00 PM Y4.6
A VERSATILE APPROACH FOR BIO-MATERIAL PATTERNING: MASKED ION BEAM LITHOGRAPHY. Kenneth Gonzalez, Dept. of Chemistry, University of North Carolina, Charlotte, NC, United States.

Biological materials play a key role in numerous medical applications ranging from tissue engineering to drug delivery systems. Surface microfabrication techniques have been widely utilized to improve the performance of biomaterials, including biomaterials. One of the most extensively investigated approaches is mechanical transfer of the microtemplates of a die into biopolymers. Although attractive, this approach has some intrinsic major shortcomings: (1) it is a two-step process including first generating the patterns on a die by standard lithographic methods and transferring the patterns into the polymer. This implies an unworkable loss of fidelity and a lack of process reproducibility. (2) only the topology of the material can be modified leaving no possibility to specifically tailor the surface chemistry of the patterns. Therefore, an alternative microfabrication method we employed was masked ion beam lithography in our study. Since it is a one-step process, the patterns can be transferred into the polymer in a controlled manner. Moreover, by selecting the right ion to implant, such as K, Na, Cs, the surface chemistry of the biocompatible material can be tailored. In our preliminary study, Cu implanted PMMA was used as a model system. The patterns produced on the PMMA film were characterized using ion beam microscopy and AFM, while the profile of the implanted ions in the film was obtained by SIMS. The effects of the pattern geometry and implanted ion species as well, on the growth of certain cells will be further investigated.

4:15 PM Y4.7
FORMATION AND CONDUCTIVE PROPERTIES OF MINIATURIZED FULLERITE SENSORS. Alexander S. Berdinsky, Novosibirsk State Technical University, Novosibirsk, RUSSIA.

Fullerene endohedral metallofullerenes (EMFs) have demonstrated potential for use in nanoscale electronics, and have shown promise as front-end detectors in radiation sensors. While these nanoscale devices hold promise, they are difficult to fabricate, and current methods for producing EMFs do not allow for precise control over the properties of the individual EMFs, such as the exact chemical composition and size. In this work, we have taken a novel approach to fabricating EMFs, using a combination of ion implantation and ion beam manipulation to create precisely controlled nanoscale EMFs. This allows for precise control over the final properties of the EMFs, and opens up new possibilities for their use in nanoscale electronics.
nm in this ion-energy range at room temperature. Between room temperature and \( \sim 200 \) C, \( \lambda^2 \) depends weakly on temperature and above \( \sim 200 \) C, the Arrhenius equation for viscous relaxation in a thin surface layer is shown to be the dominant smoothing process during erosion; the rate of viscous smoothing scales as \( \lambda^2 \). Room temperature sputtering of a commercial liquid-crystal display glass (Corning Code 1237) results in a \( \lambda^2 \) that is \( \sim 3 \) times that for the thermal oxide while \( \lambda^2 \) for an evaporated SiO2 film is \( \sim 1.5 \) times greater, suggesting that the large difference in intrinsic viscosity between these materials is not as important to corrosion as the ion-induced fluidity. Corrugations on crystalline Al2O3 exhibit a \( \lambda^2 \) similar in magnitude to that observed for the glasses but possess a much greater degree of ordering. Feasibility experiments where corrugations in deposited oxide films act as each mask for chemical transfer of the corrugation to underlying films will also be discussed.

4:45 PM Y5.4
TIME-RESOLVED X-RAY SCATTERING STUDY OF ION-INDUCED PATTERN FORMATION ON COBALT SURFACES. O. Male, School of Applied and Engineering Physics, Cornell Univ., Ithaca, NY; R.L. Hendrick, Cornell High Energy Synchrotron Source, Cornell Univ., Ithaca, NY; Min Su Yi, Kwang-Ju Institute of Science and Technology, Korea; J.M. Pomerey, Dept. of Physics, Cornell Univ., Ithaca, NY; J.D. Brock, School of Applied and Engineering Physics, Cornell Univ., Ithaca, NY.

Low-energy ion erosion of materials at low temperatures often results in the formation of surface ripples, mounds or pits with a narrow size distribution. What is particularly interesting is the potential of being a novel technique to synthesise metallic and semiconductor dots at the nanometer scale. The exact morphology of the ion-induced self-assembled pattern depends on the material structure and the ion angle of incidence, and temperature. In spite of the extensive experimental and theoretical effort in the field, our understanding of the microscopic mechanisms governing sputtering is still limited. To gain insight into this process, we used in situ grazing incidence x-ray scattering and Atomic Force Microscopy to investigate Ar ion sputtering of Co surfaces. Under ion irradiation at temperatures below 300°C, single crystal Co (0001) surfaces roughen and develop a pattern of mounds or pits. The average separation length between features, \( \lambda^i \), increases with ion dose, energy and simple temperature. Taking advantage of the high flux x-ray source available at the Cornell High Energy Synchrotron Source, we studied in detail the real time evolution of this surface pattern. Early times of the process were followed using a fast response SAXS detector with an emission \( \lambda^2 \) lower than the predictions of recently proposed theoretical models and other experimental results. At later times, the coarsening law deviates significantly from a power law. In order to explore the microscopic processes occurring during ion erosion, Kinetic Monte Carlo simulations of sputtering were performed, and the results are compared with the experimental data. The simulations point to edge diffusion as the leading cause for mound formation during sputtering at low temperatures.

SESSION Y5: NANOSTRUCTURES AND NANOFABRICATION FOR BIOLOGICAL APPLICATIONS

Chairs: Ashutosh Chilkoti and Kenneth E. Goslneaves

Wednesday Morning, November 28, 2001

8:30 AM Y5.1
NANOMETRIC PATTERNS FOR TISSUE ENGINEERING FABRICATION AND IN VITRO BIOCOMPATIBILITY. M. Bieche, 1 M. Dalby, 1 H. Johnstone, 2 J. Gallagher, 1 M.A. Wood, 2 I. McIntyre, 2 B. Oprea, 1 M. Bieche, 1 S. Assaf, 1 D.W. Wilkinson 2 and A.S.G. Curtis. 1 Centre for Cell Engineering, IBIS, Department of Electronic Engineering University of Glasgow, Glasgow, UNITED KINGDOM; 2 Department of Pure and Applied Chemistry, University of Strathclyde, UNITED KINGDOM.

Three fundamentally different methods were used to fabricate nanometric surface features on polymers or fused silica. Phase separation of binary polymer mixtures resulted in randomly distributed features whose depth and shape could be tightly controlled over large areas. Large areas were patterned by colloidal resist to give a locally random but overall uniformly pattern with very fine spikes. In contrast e-beam and reactive ion etching were used to create a set of regular spaced pillars on an orthogonal pattern. Some of the surfaces were replicated in silicon polymerisation, stereolithography, embossing, mould making, metal deposition (PS, polyethylene terephthalate, poly(methyl methacrylate) (PMM) and polylactic acid (PLA)) and polyglycolic acid (PGA) thin films were imprinted onto some of the polymers (PMMA, PGA, polyethylene terephthalate) and polylactic acid (PLA) with high fidelity. Cells were seeded onto the nanometric surfaces and adhesion, morphology and cytoskeleton investigated. Cells respond to regular features of 170/80 nm (width/depth) with reduced adhesion and changed morphology. Small nanofeatures (18 nm, 400 nm depth) made by phase separation on the other hand increased adhesion and promoted cytoskeletal differentiation. The responses of the cells are indicative that nanometric surface features are useful modifications on scaffolds for tissue engineering or for the surfaces of medical implants.

9:00 AM Y5.2
MICROFABRICATION FOR CELLULAR ENGINEERING. Mehmet Toner, PhD Center for Engineering in Medicine, Massachusetts General Hospital, Harvard Medical School, Boston, MA.

Biomedical application of microfabricated devices is no longer limited to non-living systems as genes-on-a-chip or lab-on-a-chip, recent advances in the understanding of cellular behavior in micro-environments have started to pave the way toward living micro-devices. These emerging devices are expected to become key technologies in the 21st century of medicine with a broad range of applications varying from diagnostic, tissue engineered products, cell-based high throughput drug screening tools, and basic molecular biology tools. They will also include multiple cell types and/or genetically engineered cells to investigate complex interactions between cells from different tissues. These sophisticated devices will contain micro-engineered tissue units coupled to each other by complex microfluidic handling network. Microfluidic mixing systems will also precisely regulate the composition and concentration of drugs to interact with cells. This present view will focus on fundamental aspects of integrating cells into micro-devices. Special emphasis will be placed on cellular and cell-cell interactions, and chemical and microfluidic approaches to control spatial distribution of cells on bio-compatible surfaces. Next, several general areas of applications will be discussed including liver and skin tissue engineering using microfabrication, the use of electrophoresis to create cellular arrays for rapid screening, and microfluidic cellular chemistries array.

9:30 AM Y5.3
E-BEAM PATTERNED POLY(ETHYLENE GLYCOL) FOR SPATIAL CONTROL OF SURFACE BIOACTIVITY. P. Krako, C. Sotolico, M. Lieber, Steelying Technology, New York University Medical School, NY; R. Cherry, Hospital for Joint Disease, New York University Medical School, NY, NY.

Poly(ethylene glycol) (PEG) has been used extensively in biomaterials applications to modify hydrophilicity. PEGylated surfaces typically exhibit reduced protein and cell adsorption. E-beam patterned PEG can be used to create biologically active surface features at length scales relevant to both proteins and cells. PEG films with thicknesses ranging from approximately 100 nm - 400 nm were spin coated onto silicon and glass substrates. Lithographic patterns with minimum feature sizes of order 100-200 nm were generated using a LIEBIG Scanning Electron Microscope controlled externally by an Envispec Vision system. Electron-beam irradiation crosslinks PEG rendering it less soluble in a subsequent water rinse. As such, PEG can be used in much the same fashion as traditional e-beam photoresists. This research uses electron doses ranging 1 x 10^1 to 5 x 10^1 C/cm^2 with electrons of 5-10 keV incident energy. The electron trajectories and energy-deposition profiles in the polymer thin films were modeled using Monte Carlo methods. The biophysical response was assessed using the cell binding fragment of human fibronectin (FN) together with a rabbit anti-FN primary antibody and either a goat anti-rabbit IgG FITC fluorescent secondary antibody or a 12 nm gold-labeled goat anti-rabbit IgG secondary antibody. Assessment using flowcytometry optical microscopy or backscattered scanning electron microscopy shows that the patterned PEG features control the FN adsorption on either silicon or glass substrates. Work is ongoing to understand the effects of lithographically defined spatial constraints on the adhesion, proliferation and expression of specific cells in the context of biosensing and bioengineering applications.

9:45 AM Y5.4
THE DEVELOPMENT OF SURFACE ROUGHNESS AND IMPLICATIONS FOR CELLULAR ATTACHMENT IN BIOLOGICAL APPLICATIONS. Bruce Banks, Sharon Miller, Kim de Groot, NASA Glenn Research Center, Cleveland, OH; Amy Chen, Ohio Aerospace Institute, Cleveland, OH; Manfred Sabols, Cleveland State University, Cleveland, OH.

The application of a nanosurface microscopic surface texture produced by ion beam sputtering textures the surfaces of polymer implants has been shown to result in significant increases in cellular attachment as compared to smooth surface implants in animal studies. A cooperative program between NASA and the Cleveland State University Foundation has been established to evaluate the potential use of atomic oxygen texturing to improve osteoblast attachment to surfaces.
that have been microscopically roughened. The range of surface
textures that are feasible depends upon both the texturing process
and the duration of the treatment. To determine whether surface
roughness increases or decreases with treatment duration, an effort
was conducted to examine the development of such surface textures
produced by various physical and chemical erosion processes.
Both experimental and computational methods were needed to
explore the growth of surface texture with treatment time. Surface
texturing by means of abrasive grit blasting of glass, stainless steel
and polyethylene methacrylate was examined to measure the growth in
roughness with blasting duration by surface profilometry
measurements. Laboratory tests and computational modeling was also
conducted to examine the development of surface roughening caused
by directed and isotropic atomic oxygen attack of Kapton polycarbonate
and Acryl (dichloroacetyl chloride). For the atomic oxygen texturing
tests, atomic force microscopy was used to measure the development
of surface texture with atomic oxygen fluence. The results of all the
tests and computational modeling support the premise that
deposition of atomic oxygen obeys Poisson statistics. The results
indicate that surface roughness does not saturate but increases as the
square root of the treatment time.

10:30 AM *Y5.5
NANOPOROUS MICROFABRICATED MEMBRANES: FROM
DIAGNOSTICS TO DRUG DELIVERY.
Tejaj Ashwin Desai, Univ. of
Illinois-Chicago, Chicago, IL.

Membrane-based biochemical separations are highly desirable for
many biomedical applications ranging from biosensors to drug
delivery. The ideal approach for implementing molecule size-based
selective membranes would be to design a synthetic membrane that has a
collection of monodisperse nanopores, of molecular dimensions, that span
the complete thickness of the membrane. These "molecular filters" could then be used to separate small molecules on the basis of size,
for example, viruses and proteins during the blood fractionation
process or the blocking of antibodies and complement molecules from
encapsulated xenograft human cells. However, pore sizes of >5nm have been
difficult to achieve via normal lithographic processes. We have circumvented
this limitation by using a combination of photo-lithography and selective removal of sacrificial layers, leading to silicon membranes with pore sizes down to several
nanometers. The technology of microfabrication can be used to create membranes with a multitude of pore configurations and arrangements, capable of high densities (>10^9 pores/cm^2) and uniform pore sizes
(<5%). In this presentation, we will describe the fabrication and application of photolithographically defined nanopore membranes consisting of arrays of parallel rectangular channels with precise dimensions in the 7-10nm range. These membranes have been used to perform size based exclusion and controlled diffusion of model biomolecules. In addition to tightly controlled pore size distributions (<1% over a 4-inch wafer), these membranes take advantage of silicon's biocompatible material properties such as biological, thermochromic, and mechanical stability.

11:00 AM *Y5.6
DESIGNING IN VITRO PATTERNED NEURONAL NETWORKS.
Bruce C. Wieslander, Gregory J. Brewer, John C. Chang, Yoonkey Nam.
1 University of Illinois at Urbana-Champaign, Dept of Electrical and
Computer Engineering, Urbana, IL. 2 Southern Illinois University School of Medicine, Dept of
Medical Microbiology, Springfield, IL.

Through the use of microstamped patterns of polyethylene against
covalently linked backgrounds of polyethylene glycol, we have been able to maintain patterns of neurons for up to a month in culture. We have demonstrated the ability to use patterning technology in combination with planar microelectrode arrays to confine the neurons to narrow (10 um or 40 um) tracks which intersect the electrodes and to record spontaneous electrical activity (action potentials) from them. We plan in the future to determine how sparse a network can be and still maintain functional electrical activity. This work is intended to provide a technological basis for robust, repeatable and designable neural networks from which one could study basic neuroscience or construct a neural computer. Supported by NIH grants R21 NS 3861 7-01 and R03 RR 13329-01 and fellowship F30 MH 12897.

11:30 AM Y5.7
INTEGRITY OF PROTEIN MICROPATTERNS ON
DEGRADABLE POLYMER SUBSTRATES. K.E. Schmedley and
K.E. Ulrich, Dept of Chemistry, Rutgers University, Piscataway, NJ.

Repair of the peripheral nerve system is a complicated issue involving
both topographic and chemical cues. When injury occurs to the nerve,
regrowth of the affected cell must be directed along its original path
to function to resume. Proteins that chemically elicit cell-cell
attachment, such as laminin, were physically deposited to promote

neurite adhesion and outgrowth in a spatially specific manner. The
micron-sized, protein-based patterns were created on polymeric
substrates using microcontact printing, or soft lithography. Previous
work focused on nerve cell outgrowth on poly(methyl methacrylate),
whereas this study will focus on biodegradable polymer substrates
including poly(hydroxybutyrate), poly(caprolactone) and poly(
caprolactone). The protein microarrays adherence as function of
degradation was primarily probed using nerve cells, although the
pharmacological characteristics of the substrates will be evaluated by
scanning electron microscopy and x-ray photoelectron spectroscopy.

SESSION Y6: FUNCTIONALIZATION AND
ORDERING OF 1D AND 2D STRUCTURES.
Chair: Kenneth E. Gonsalves and Wilhelm H. Brueger.

1:30 PM Y6.1
SURFACE FUNCTIONALIZATION OF CERAMIC NANO-
PARTICLES: APPLICATION TO ION- SENSING AND
GAS-SENSING DEVICES. Marie-Isabelle Burnet, UMR 6288
CNRS, University of Limoges, Limoges, FRANCE.

Tailoring the surface properties of nanosized ceramic particles is a
challenging problem faced by scientists working in the fields of hybrid
organic-inorganic nanocomposites (dispersion problems) and
ceramic-based electronic transducers (selectivity and stability
problems). We will review methods for grafting molecules like
hydroxy silane, chlorosilane, and hexamethyldisilazane on various
types of nanoparticles including Si3N4, Si3N4-O-TiO2, and SiO2.
FTIR spectrometry is used as primary investigation tool. In terms of physical properties
modification, we will concentrate on the optimization of ion-sensitive PEI and gas sensors.
The beneficial effect of hydrophilic and chlorinated grafted on Si3N4 and Si3N4-O-TiO2
used as ion sensitive membranes will be demonstrated. Then the reduction of
humidity effects on HMDS-grafted immobilized TiO2 and SiO2 powders used for screen-printed CO sensors will be reported.
This work has been partially funded by the European Commission
under the Brite-Euram and IST programmes.

2:00 PM Y6.2
BIOSENSING AND BIOELECTROCHEMICAL PATTERNING USING
NANOPARTICLES. Ashutosh Chilkoti, Duke University, Department of
Biomedical Engineering.

I will describe the use of nanoparticles in the fabrication of biosensors and
nanoscale biomaterials. In the first application, we have explored the
use of gold colloids in suspension as a cokrimetric reporter of the
intial phase of environmental responsive biopolymers. We observed that gold nanoparticles, once which an ELP is
immobilized, exhibit a large red-shift in their absorbance spectrum
due to aggregation of the colloids due to the hydrophilic-to-
hydophobic phase transition of the immobilized ELP. This method
provides a simple and convenient colorimetric method to study the influence of the solution environment, interfacial properties and grafting methods on the transition properties of environmentally responsive polymers at the solid-water interface. We have also immobilized gold nanoparticles onto glass slides, functionalized these surfaces with biological ligands, and shown that these colloidal-decorated surfaces enable ligand-binding to be detected by the shift in the absorbance spectrum of individual colloids. This assay is analogous to conventional SPR with the added advantage of being performed in widely available, low-cost UV-visible spectrophotometers. Finally, we have detected the photostable, near-infrared emissive character of nanocrystal-ligand composites and demonstrated that these nanoparticles are useful for applications that range from surface-enhanced spectroscopy to the bottom-up fabrication of nanostructured biofunctionalized surfaces using chemical and biological self-assembly.

2:30 PM Y6.3
STABLE ADSORPTION OF LIPID VESICLES ON MODIFIED GOLD SURFACES. Santiago Solé-Lluch 1, James L. Thomas 2. Columbia University, Dept of Chemical Engineering, New York, NY.

The use of vesicles as amplifiers in biosensors is receiving increasing attention. Because vesicles may entrap thousands of reporter molecules, strong signal amplification can be obtained if a small number of analytes can simply release the entrapped reporters. Surface immobilization of vesicles with sensitivities for different analytes indicates promise for simultaneous amplified detection of a number of analytes on a single chip. To achieve this goal, vesicles must first be stably adsorbed to a surface, without rupture. We have varied vesicle composition and charge (phosphorylcholine, phosphorylcholine-choline-phosphorylcholine acid or 4 mol% ra) and solution ionic strength, to study the adsorption of fluorescent vesicles to gold, glass, and gold modified with chemically acrylic polymer. Surfaces were characterized with single-resolved X-ray photoelectron spectroscopy (XPS), and vesicle integrity and behavior was studied using entrapped and/or lipophicul fluorescent markers. Diffusion coefficients (by photobleaching recovery) and vesicle fission (by energy transfer) were monitored using confocal fluorescence microscopy. Finally, in a "proof of principle" release of a self-assembling entrapped reporter dye (calcine) by the detergent Triton X-100 was followed in real time.

4:00 PM Y6.6
NANOFABRICATION AND CHARACTERIZATION WITH THE ULTRAHIGH VACUUM SCANNING TUNNELING MICROSCOPE. Grant L. Surfa, Ellen Liu, Jin Xu, and J. W. Lyding. Beckman Institute for Advanced Science and Technology, University of Illinois, Urbana, IL.

Recently, ultra high vacuum (UHV) scanning tunneling microscopy (STM) is used to selectively desorb hydrogen from the Si(100)/2×1 surface so as to make atomic scale patterns and selectively adsorb molecules. In order to understand well the chemical interactions between the dangling bonds on the surface, the electronic properties of single dangling bonds were investigated on the Si(100)/2×1 surface by UHV-STM. On the N type Si(100)/2×1 surface, feedback control lithography (FCL) created single dangling bonds and some of the natural dangling bonds were neutral. On the other hand, both FCL created and natural single dangling bonds are neutral on P type Si(100)/2×1 surface. Current image tunneling spectroscopy (CITS) measurements demonstrate different electrical properties on them. Specially, the STM images of the single dangling bonds with a fixed negative charge display dramatic voltage dependence with Friedel oscillations around these dangling bonds in the empty state images. Isolated Cobalt phthalocyanine (CoPc) molecules were selectively adsorbed on both the natural dangling bonds of the Si(100)/2×1 surface and FCL created single dangling bonds on the Si(100)/2×1 surface. On the Si(100)/2×1 surface, three major adsorption configurations were observed. Electronic character of CoPc but possessing different central structural features. However, images obtained on the Si(100)/2×1 surface correspond to molecular rotation of CoPc parallel to the surface. STM, STS, CITS and molecule modeling are used to investigate the different interactions between CoPc and these two Si substrates, as well as their effects upon the electronic charge distribution and the geometric configurations of the adsorbed CoPc molecules. This study may be useful for making molecular-scale RAM.

4:15 PM Y6.7
PREFERENTIAL ADHESION OF GOLD NANOPARTICLES USING LITHOGRAPHICALLY PATTERNED SUBSTRATES. Johan Pål, Mohammad S. Kabir, S.H. Magnus Persson, Chalmers University of Technology, Dept of Microelectronics and Nanoscale, Gothenburg, SWEDEN, Mathias Brand, Liverpool Uni, Dept of Chemistry, Liverpool, UNITED KINGDOM.

In the area of molecular electronics, the electrical properties of nanoparticles and molecules connecting them is a big issue, but there exists considerable problems in making well defined electrical measurements on them, and there are often difficulties in knowing what particles the measurements are really taking place. By using silicon substrates patterned with silanes or silazanes having different endgroups by chemical etching and electron beam lithography, small arrays of gold nanoparticles have been assembled between narrowly spaced electrodes. This enabled the possibility to make well defined electrical measurements of the nanoparticles, and also conjugated diaphlides and diene with interesting electrical properties.

Department of Medicinal Chemistry, Department of Biomedical Engineering Purdue University, W. Lafayette, IN.

Nature assembles nano-scale components using molecular recognition. In the case of DNA, hydrogen bonding is the driving force behind the formation of complementary pairs of single-stranded (SS) DNA to hydrogenize into a double-stranded (DS) DNA. For the case of DNA, a single strand sequence can be attached to the device surfaces, which is complementary to a single strand sequence previously attached to a patterned surface. Using the natural hybridization devices are expected to be assembled. Following the case of DNA, a single strand sequence can be attached to the device surfaces, which is complimentary to a single strand sequence previously attached to a patterned surface. Using the natural hybridization devices are expected to be assembled. When successful, this approach can be used to assemble micro and nano-scale electronic circuitry including heterogeneous integration of materials.
DIRECT PATTERNING OF SURFACES WITH COLLOIDAL PARTICLES USING OPTICAL TWEETERS. Dirk L.J. Vosse, Jacob P. Hoogenboom, Karin Overeijdt, and Alfons van Blaaderen, F.O.M. Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS. We describe a method for patterning substrates with colloidal particles in any desired pattern. By using optical tweezers particles are brought from a reservoir to a surface that carries a surface charge opposite to that of the particles. We show that using this technique large, two-dimensional patterns can be created, where the pattern can be manipulated as a single particle level. Furthermore, we show that this method works for a large variety of functionalized (core-shell) colloidal particles. Particles that can be manipulated by means of optical tweezers include particles that are interesting for photonic applications like high-refractive-index (ZnS) core silicium shell particles, metallic (Ag) core - silicium shell particles, fluorescently labelled particles and small (several nanometers large) gold particles. Particle sizes range from several nanometers to over a micrometer. We show how these two-dimensional patterns can be dried for further processing and how these patterns can be used in subsequent three-dimensional epitaxial crystal growth. The method works relatively fast, is cheap, can be fully automated and can in principle be used to build three-dimensional structures.2:45 P.M. YE.9 PATTERNING OF QUANTUM DOTS USING NANOPOROUS ALUMINA. N. N. Paser, M.B. Tiol, B.M. Speckman, S.D. LeLumundere, and T.L. Jennings, The Aerospace Corporation, Los Angeles, CA. Simple, high-throughput, low-cost methods for the deposition of patterned nanocrystal arrays on substrate surfaces is necessary for the development of the next generation of electronics based on nanoscale devices. As the need for faster computer speed, computing ability, and reduced power requirements increases, device dimensions in integrated circuits must continue to shrink. Miniaturization of magnetic- and silicon-based devices is becoming increasingly difficult due to limitations of optical lithography and due to the problems associated with high device densities, such as “cross-talk” and inadequate heat dissipation. Theoretically, ordered arrays of quantum dots can be used to build complex computing systems, which, if traditional electronics are no longer connected, do not rely on current flow. The ability to deposit and/or grow semiconductor quantum dots in appropriate nanometer arrays is currently the single greatest technological hurdle to be overcome before these technologies can seriously be considered. We report here a simple, rapid, and inexpensive method for producing nanorays of GeSe/Se nanocrystals on quantum dots, using porous alumina. Highly ordered arrays of nanocrystals, approximately 20-200 nm in diameter, can be produced in very thin sheets of aluminum metal using a carefully controlled condensation process. We have successfully trapped GeSe/Sn nanocrystals (approximately 30 nm in diameter) within these highly ordered nanocrystals, and have characterized the optical properties of the trapped nanocrystals. We will describe the details of this process and discuss our spectroscopic results.

SESSION V7: POSTER SESSION MATERIALS AND NANOFABRICATION TECHNIQUES FOR ELECTRONIC AND BIOLOGICAL APPLICATIONS Chair: Ladi Methani

Wednesday Evening, November 28, 2001 8:00 P.M.

Exhibition Hall D (Hynes)

Y7.1 EFFECTS OF MASK MATERIALS ON NEAR FIELD OPTICAL NANOLITHOGRAPHY. Shari McNab, Richard Blakie, University of Canterbury, Dept Electrical and Electronic Engineering, Christchurch, NEW ZEALAND.

Sub-diffraction-limited resolution has been reported for optical lithography in the near field of an amplitude mask [1] and simulations predict resolution down to 10nm [2]. In addition, an evanescent interferometric lithography (EIL) technique has been proposed for patterning periodic nanostructures [3]. The studies to date have employed standard metallic masking materials, chrome or nickel. We have performed a simulation study on the effects of different masking materials on these techniques. Chrome, gold, tungsten and silicon have been chosen as common microelectronic materials that can be patterned down to the nanoscale. For near field amplitude masks it is found that chrome is an excellent material at blue/UV wavelengths, due to its small skin depth. Gold is too transmissive to be considered. Tungsten has a small skin depth like chrome, although its dielectric behaviour at blue/UV wavelengths leads to image reversal phenomena that may be undesirable. Image reversal is even more pronounced for silicon masks, but significant field enhancement effects are observed that may be beneficial for reducing exposure times. Finally, the mask material issues are more complicated, as this technique relies on surface-photon-induced resonant enhancement of the evanescent fields behind a grating. For metallic materials, chrome is again superior to gold, and significant field enhancements are also present above the grating cutoff. For silicon the resonant enhancements can be very large and narrow band, which may be of great advantage. For example, intensity enhancements of more than 20 times are predicted for 278 nm silicon gratings illuminated at a wavelength 10 percent higher than cutoff. These issues will be discussed in detail. 1. Akinai, et al., Appl. Phys. Lett. 75, 1881 (1999); Goodberlet, Appl. Phys. Lett. 76, 627 (2000).

Y8.2 PYROELECTRIC EMISSION FOR LITHOGRAPHY. Changwook Moon, Wonbong Choi, Kang Bae, Dongwook Kim, Kyung Yoo, Samsung Adv Inst of Tech, Suwon, Kyonggi, KOREA.

1:1 electron projection lithography with wide projected area was studied by patterning images and measuring emission current utilizing pyroelectric electron emission from ferroelectric materials. It was observed that the pyroelectric emission is suitable for a 1:1 projection lithography applications. Focused ion beam (FIB) electron projection were patterned on the e-beam resist by controlling magneto-electric system in vacuum. Theoretically, pyroelectric electron emission has the potential to give a perfect result in a 1:1 electron projection lithography. The 1:1 PEL (pyroelectric electron lithography) method has several advantages over conventional lithography technologies such as pyroelectric emitter will be used as an electronic source due to its recycle after heating above Tc and 1:1 PEL can increase throughput due to its capability of wide area electron projection. We have demonstrated 1:1 electron projection lithography on electron resist by heating a pyroelectric BiFeO3 emitter with a grid pattern. It was observed that a heating process was not necessary for pyroelectric emission when high Py materials are used, i.e., pyrocrystalline BiFeO3. Heating the emitter above its Tc during the lithography process eliminated the degradation of the pyroelectric emission effect. An approximate relationship among emitter-collector distance, applied DC voltage, and magnetic field was studied systematically. This paper will describe new design concepts for 1:1 PEL and provide controlling factors for obtaining fine patterning. Y7.3 CHARACTERIZATION OF La/Ba/Co MULTILAYER MIRRORS FOR X-RAYS BELOW 1000EV. Christian Spies, Wolfgang Joeger, University of Kiel, Center for Microanalysis, Faculty of Engineering, Kiel, GERMANY; Carsten Michene, Joerg Wissen, Ruediger Bormann, Institute of Materials Research, GKSS Research Center, Geesthacht, GERMANY; C. Norwik, HASYLAB, DESY, Hamburg, GERMANY.

Metastable multilayer systems based on metal-normal metal combinations with layer thicknesses in the nanometer scale are of interest for advanced X-ray optical applications. We have fabricated La/Ba/Cu multilayer films by magnetron sputtering for the use as X-ray mirrors at energies below 190 eV, particularly for the detection of boron K X-rays at 180 eV, and compared them to Mo/Ba multilayers that are currently the best-performing multilayers for this energy range. Transmission electron microscopy, low-angle X-ray diffraction and synchrotron soft X-ray reflectometry at energies between 50 eV and 525 eV were used to analyze the structure and interfaces of the multilayers, their thermal stability up to 800°C, and their performance as X-ray optical components. In general the microscopic structure of the layer systems after deposition is characterized by an excellent structural periodicity and interface quality. Depending on the fabrication process, the interfaces between the individual amorphous layers may show a different roughness. Only small fractions of oxygen and carbon are present in the multilayers as could be shown by energy-dispersive X-ray microanalysis. End- X-ray photoelectron spectroscopy. Both the peak reflectivity and the spectral purity are found to be significantly improved indicating that La/Ba/Cu multilayers have a high potential to replace state-of-the-art Mo/Ba/Cu multilayers in many X-ray optical applications. For 100 eV multilayer systems were also compared by laboratory XRF measurements of the boron K emission using samples of Bc and of BPSG (borophosphosilicate glass). For the La-based multilayer systems the improvements of the peak intensity is only the lower limit of detection amount to about 64% and 29%, respectively.
Y7.4 NOVEL FLUOROCARBINOLS FOR 157 nm PHOTOLITHOGRAPHY. Hilmar Keen, Young C. Bae, Kazuaki Douki, Dirk Schmaljahn, Patrick E. Spencer, Vishali R. Vohra, Xiang Qian Liu, and Christopher K. Ober, Cornell University, Dept of Materials Science and Engineering, Ithaca, NY.

157 nm photolithography is the foremost candidate in next generation resist technology to date. This requires a reconsideration of the fundamental understanding of how light interacts with and is absorbed by the resist material of the next generation of resists. This study was initiated by our findings in excellent etch resistance of hexafluoroacetone modified poly(allylamine), which has been utilized to provide good transparency and solubility switch. Fluorinated (or perfluorinated) polymer is known to be very sensitive to etching. This can be protected by more desirable protecting groups, such as dihydropropargyl, to yield relatively transparent tetrahydropropargyl (THP) at 157 nm. However, the most promising strategy is to use the photoresist materials that have been applied to 438 nm photoresists. Our system is based on monomers currying the hexafluoroisopropyl alcohol (HFIPA) group. This concept has been first introduced in the design of poly(pentafluorobased) resists for 248 nm. Unfortunately, protecting groups used in these cases are too absorbent at 157 nm. It has been shown that alkoxyl ethers are the most suitable groups for protection of HFIPA groups. In order to achieve a material with good chemical amplification, two-photon resists, three-dimensional microfabrication, volume shrinkage, and wet etching were used. The concept of protecting the polymer by using HFIPA modified styrenic monomers will show that our new resist platform is excellent candidates to push photolithography closer to the 70 nm node.

Y7.5 3D MICROFABRICATION IN A CHEMICALLY AMPLIFIED POSITIVE RESIST. Tingyu Yu and Christopher K. Ober, Materials Science and Engineering, Cornell University, Ithaca, NY, Stephen M. Kisselher, Wenhui Zhou, Seth R. Meeder and Joseph W. Perry, Department of Chemistry, The University of Arizona, Tucson, AZ.

Three-dimensional microfabrication has a wide range of possible applications for micromachining structures such as light-waveguides, microfluidic devices, MEMS and data storage. Two-photon lithography does not allow the fabrication of structures not feasible with conventional single-photon lithography but also exhibits greater spatial resolution than other three-dimensional fabrication techniques as currently practiced in. In contrast to UV lithography, where the photoresist serves only as a pattern transfer layer, in 3D lithography, the photoresist itself is the final structure and is utilized for pattern transfer. Thus, the resist systems should not only be two-photon sensitive but also possess some necessary properties to meet the requirements of the applications listed above. From early work on two-photon three-dimensional fabrication, volume shrinkage and warping of solid images formed in these processes were identified as critical issues where the method can be improved. Little research has been carried out to identify a more suitable system for three-dimensional microfabrication. We focus on developing a solid-state, chemically amplified positive-tone resist system which offers reduced shrinkage and greater pattern versatility by using a different solubility switch mechanism. Here, we will report the design and microfabrication of an optical grating structure with aspects of channels buried below the surface and some key processing conditions will be discussed as well.

Y7.6 NOVEL MATERIALS FOR 157 NM AND EUV LITHOGRAPHY. Alyxandra H. Hammond, Junyan Dai, Christopher K. Ober, Cornell University, Ithaca, NY; Francis M. Hosfield, Agere Systems, Murray Hill, NJ.

The design and synthesis of lithographic materials for 157 nm and extreme-ultraviolet (EUV) lithography has been a challenge. Polymers and small molecules traditionally used for lithography are absorbent at these wavelengths. Carbon double bonds and carbonyls are opaque at 157 nm in the absence of neighboring electron-withdrawing groups. Few elements can be used in an EUV photore sist due to absorption requirements and resist characteristics are restricted to the use of elements such as carbon, hydrogen, and silicon for these platforms. For example, oxygen, an element of crucial importance in earlier resist generation materials, absorbs highly at 15 nm and therefore, its use in EUV lithography. Here, we will report on the design, synthesis, and properties of new silicon-containing block copolymers and random copolymers for EUV lithography. In addition, we wish to report on fluoride and silicon-containing dissolution inhibitors for 157 nm lithography. Initial studies on our EUV resists as well as dissolution rate studies on our 157 nm dissolution inhibitors will be discussed.

Y7.7 SUPERCRITICAL CO2 DEVELOPMENT FOR ADVANCED PATTERNING OF RESIST AND DIELECTRIC MATERIALS. Victor Q. Pham, Ginn L. Weibel, Alyxandra H. Hammond, Christopher K. Ober, Cornell University, Dept of Materials Science and Engineering, Ithaca, NY; Hilton Bryce Lewis, Karen K. Gleason, MIT, Dept. of Chemical Engineering, Cambridge, MA.

As sizes of patterned features in polymer resists become smaller (and aspect ratios become larger), the concept of a post-development supercritical drying step has been suggested to prevent pattern collapse due to surface tension. A model photoresist system, tetrahydropropargyl (THP) polymer, tetrahydropropargyl polymer with 100% of the THP groups converted to 1,3,4-thiapropyl groups (THPMA-F7MA), was synthesized in both block and random copolymers and shown to be highly compatible with 193 nm and E-beam exposure technologies. Well-defined 100 nm features have been achieved when the block copolymer was developed in supercritical CO2, eliminating the need for organic developers or a drying step. With increasing understanding of polymer-CO2 interactions and subsequent process optimization, higher resolution features are expected to demonstrate technological advantages over wet development. An interferometric dissolution rate monitor (DRM) was built to probe the kinetics of polymer dissolution in SCF CO2.

Our high-pressure system has yielded interesting and reasonable results including equilibration behavior of CO2 liquid converted rapidly to supercritical in the processing chamber. In addition to resists, a patternable dielectric material was used for post-exposure bakeup in CO2. The concept of a post-exposure bakeup will be shown to possibly eliminate the need of a sacrificial resist and several processing steps in IC manufacturing. Insights to the CO2 equilibration process and an understanding of CO2 interactions with fluorinated materials are instrumental to our current efforts toward the adoption of dry lithography.

Y7.8 DESIGNING PHOTORESIST SYSTEMS FOR MICRO-LITHOGRAPHY IN CARBON DIOXIDE. Dave Flowers, Univ of North Carolina-Chapel Hill, NC; Chris McAdams, Micell Integrated Systems, Raleigh, NC; Eric Hoggan, Ruben Carbonell, North Carolina State Univ, Dept of Chemical Engineering, Raleigh, NC; Joseph M. DeSimone, Univ of North Carolina-Chapel Hill, NC; Department of Chemistry, Chapel Hill, NC; North Carolina State Univ, Dept of Chemical Engineering, Raleigh, NC; Micell Integrated Systems, Raleigh, NC.

Currently, the microolithography industry creates large amounts of organic solvents and produces organic waste products that need to be handled by environmentally friendly means. Using carbon dioxide can possibly eliminate the majority of these waste solvents as well as eliminate the image collapse problems shown with aqueous base development. We will discuss the use of carbon dioxide to replace the most hazardous steps of the micro-lithography process, spin coating and developing. However, before CO2 can replace conventional solvents, photore sist systems must be designed and synthesized to be compatible with CO2. These photore sist systems must not only be soluble in liquid CO2 to ensure that thin uniform coatings can be produced by spin coating while maintaining characteristics of conventional resist systems such as low absorbance, high sensitivity, solubility contrast, good resolution, and etch resistance. In this paper we will present our efforts to create these photore sist systems for 158nm and 130nm lithography by using fluorinated components of conventional resist systems thus rendering them soluble in CO2. Fluorine-based acrylates have been used as a resist for the 158 nm resist system. However, the 152 nm resists we are designing are fluorine-based norbornyl copolymers with tetrafluoroethylene, maleic anhydride, or 2 trifluoroethyl acrylates. Currently, the key issues are making these systems both soluble in liquid CO2 and while maintaining characteristics of conventional resists. We have also designed a liquid CO2 soluble phenol-based initiator, 2,2- perfluoroethyl-4,6-dimethyl benzoyl peroxide, which has been shown to be effective in reducing the clearing temperature of the tetraethyl lead resists.

Y7.9 NOVEL EQUILIBRIUM LAYER-BY-LAYER GROWTH OF BINARY COLLOIDAL CRYSTALS. Christina S. Christy, Krassimir P. Velikov9, Roel Dullens and Alfons van Blaaderen.9 "Physics and Chemistry of Condensed Matter, Delft Institute, Utrecht University, Utrecht, THE NETHERLANDS." 9FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS.
A mixture of submicron colloidal particles of two sizes can self-organize into binary crystals, which depending on the size ratio and concentration, can be of different symmetries. Colloidal crystals with lattice constants comparable to the wavelength of visible light are important for applications and processes as diverse as photonic crystals, chemical sensors, lithography, surface enhanced Raman scattering, and the creation of colloidal materials. However, binary colloidal crystals have not been used for these applications mainly due to lack of control in growing them. Here we present a method to grow binary colloidal crystals in a controlled way, through a simple single-layer deposition procedure with a stoichiometry of large (L) and small (S) particles of LS$_2$ (atomic analog AlB$_2$) and unexpectedly LS. In addition, we observed the formation of an LS$_2$ superstructure, which is not identified yet to any known molecular compound or alloy. Both the binary crystals with a stoichiometry of L$_2$S and L$_2$S$_2$ can be grown without stacking faults in this process. Finally, by using spheres with different composition, one component can be removed. As an example, we demonstrate the synthesis of a hexagonal non-closely packed colloidal crystal. As the method presented is quite general and can be extended to include more sizes, it will lead to a significant increase in the possible symmetries and compositions achievable for colloidal crystals.

Y7.10 EFFECT OF AI CONCENTRATION ON GROWTH OF ANTIPOHOTIC IN T$_x$Al$_{1-x}$Y$_{0.3}$Sc$_{0.7}$O$_3$. Hideki Katsurayama, Yoritoshi Minamimoto, Hideaki Tsubura, Osaka University, Dept. of Adaptive Machine Systems, Osaka, JAPAN.

In many intermetallic compounds with ordered structure, antiphase boundaries (APBs) are formed during the ordering process. Since the APBs can trap dislocations and assist in the self-process of dislocations, it is possible to make regular arrangement of dislocations in a nanoscale by controlling the morphology of APBs, i.e., size and shape of antiphase domains (APDs) which are regions divided by APBs. Such regular arrangements of dislocations are expected to give unique mechanical properties, for example, completely reversible plasticity. T$_{1/2}$Al intermetallic compound is one of the most useful materials to make such mechanical properties real. However, no attempts have been done to control the morphology of APBs in T$_{1/2}$Al. In this study, T$_{1/2}$Al crystals with stoichiometric (T$_{35}$S$_{65}$ %Al) and Al-rich (T$_{35}$S$_{65}$ %Al) compositions were annealed at various temperatures (973–1123 K) subsequently to disordering treatment. And the effects of Al-concentration on the change in the morphology of APBs were investigated. Remarkable effects of Al concentration were found. Firstly, growth rate of APDs in the Al-rich crystal was several times as high as that in the stoichiometric crystals. Secondly, time dependence of APD size varied during annealing only in the Al-rich crystal. While the APD size was always proportional to the square root of the annealing time (t) in the stoichiometric crystal, the time exponent became smaller than 1/2 at later stage in the Al-rich crystal, indicating the existence of dragging force acting to the motion of APBs. Additionally, APBs aligned along [0001] and 1100 planes were observed in both the Al-rich and stoichiometric crystals at the lowest temperature. The results are discussed in the context of APBs in these compounds are focused on the effects of Al concentration on driving force and mobility of APBs.

Y7.11 AFM STUDIES OF SURFACE FRACtURES OF COMPOSITION B ENERGETIC MATERIALS. Y.D. Lanseretti, U.S. Army TARCO, Aberdeen Proving Ground, Aberdeen, MD.

In this paper the characteristics of TNT crystals in Composition B (50% cyclotrimethylene (RDX), 40% TNT and 10% wax) at the fracture surface of energetic materials are presented. The size of the TNT crystals has been determined by analyzing the surface structure after mechanical failure of the Composition B. The sample of melt-cast Composition B used for the AFM studies was fractured at 40 K in an ultrahigh vacuum. AFM examination of the topography of the fracture surface of the Composition B reveals fracture across columnar grains of the TNT. The width of the columnar TNT grains range from ~1 μm to ~2 μm. The height of the columnar TNT grains range in size from ~50 nm to ~1000 nm. We have introduced AFM techniques to characterize the fracture surface topography of Composition B obtained at high acceleration. Using AFM we have measured the size of the columnar TNT grains of Composition B and have determined that the fracture of the Composition B occurs within the TNT.
due to the participation of functional groups in coordinating Li ions. In this work we present new results obtained by studying the addition of LiClO$_4$ when this salt is included in the hybrid mixture with amounts corresponding to the limit of maximal homogeneous incorporation. This corresponds to the composition CH$_3$PA$_8$/LiClO$_4$ = 0.6/1/0.8M. For this composition, VEC-DIC microscopy of the first three layers of the films showed that each layer has oriented patterns with angles of exactly 60 degrees between the planes. On the other hand, DRX showed that some sharp new peaks appear with the incorporation of the lithium salt. The same signals appear with the addition of lithium chloride, but no peak attributable to the corresponding lithium salt was observed in films with homogeneous incorporation of the salt. These results in combination with FTIR analysis of the products indicates that lithium ions behave as strong structure directing agent and allowed us to propose an interaction scheme comprising the components of this hybrid system.

Acknowledgments: Projects a) Bondeley 1010525, 1010924 and 292094.

Y.7.15 POLYMERIC ALL SOLID STATE NANOCAP BATTERY. Steven E. Bullock, and Peter Koffman, University of Maryland, Dept of Materials and Nuclear Engineering, College Park, MD

The goal of the proposed research is to synthesize A/B/C trilobal copolymer - metal nanocomposites and evaluate their electrical properties for the fabrication of all-solid state nanocap batteries. The use of processing a polymer electrolyte would allow the production of a thin film battery that could be wound into coils or pressed into sheets. The A/B/C trilobal copolymer battery would exhibit a lamellar microphase separation, with anode, polymeric electrolyte and cathode as the A, B and C blocks, respectively. The A block (polymeric backbone) forms the anode material and the B block (polymeric backbone) is the electrolyte. In the C block (functionalized boron) it is the cathode material and utilizes a hydride reduction. Casting the synthesized polymer from a solvent results in a self-assembled lamellar A/B/C nanomaterial, which is equivalent to many battery cells in series. Microstructure and electrical properties characterization tools are employed to evaluate the battery system’s performance.

Y.7.16 ELECTRIC FIELD ASSISTED DEPOSITION AND DETERMINATION OF THE ELECTROSTATIC PROPERTIES OF CdSe NANOPARTICLES. Mohamed A. Islam and Irving P. Herman, Columbia University, Research Science and Engineering Center and Columbia Radiation Laboratory, New York, NY.

CdSe nanoparticles of 3.2 nm diameter capped by trimethylphosphine oxide were deposited on Au electrodes by the assistance of strong electric field. A pair of Au-on-S electrodes separated by 1.4 mm was submerged in the nanoparticles dispersed in 90% hexane and 10% cyclohexane as the order by which the nanoparticles were applied in a dark room. When the electrodes were submerged in only the solvent, current was measured to be ~ 1 - 2 nA nanomperes. When the nanoparticles were added to the solvent, current immediately jumped up to the 50 - 100 nA nanomperes range, depending on the nanoparticle concentration and the size of the electrodes. The current was found to increase linearly with the applied voltage, electrode area and nanoparticle concentration. The nanoparticles were deposited on the positive electrode, indicating that the nanoparticles charged in these experiments. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used to determine the morphology of the deposit. The nanoparticles make micron sized lines on the electrode. The islands are few hundred nanometers in height and have sharp edges indicating that the nanoparticle assembly may be crystalline. The total number of particles deposited in a given time and the deposition rate are determined from SEM and AFM.

This work was supported by the MRSEC program of the National Science Foundation, Contract No. DMR-9809687.

Y.7.17 EXCIMER LASER MICROMACHINING OF WIDE BAND GAP SEMICONDUCTOR WAVEGUIDE FOR NANO-SCALE CAGED MOLECULE DRUG DELIVERY. Mona R. Safadi, Claudine A. Johnson, Alexander C. Gagnon, Gregory W. Timp, Department of Electrical and Computer Engineering/Biomedical Engineering, Wayne State University, Detroit, MI. Gary Abrams, Raymond Iozzi, Peter McAllister, School of Medicine, Kreger Eye Institute, Department on Neurosurgery, Wayne State University, Detroit, MI; Rama N. Naik, Department of Physics, Wayne State University, Detroit, MI; Vaman M. Naik, Department of Natural Science, University of Michigan-Dearborn, MI.

The fabrication of a broad spectrum AIN thin film waveguide used in a nanosized caged neurotransmitter based microfluidic drug delivery chip is reported. The wave guide will be used in an artificial retina system along with other applications where spatially controlled movements of neurotransmitters are needed. Kef Excimer laser micromachining technology is employed in the development of the wide band gap waveguide. Highly textured AIN thin films are grown on C-plane sapphire by plasma source molecular beam epitaxy (PSMBE). A 288 nm Excimer laser beam projected through a patterned stainless steel mask and through an objective lens down to 0.1 times of the actual pattern of the mask on to the AIN/sapphire substrate. The irradiation energy per pulse, frequency, number and pulse, pulse, pulse duration were held constant. Atomic force microscopy and scanning electron microscopy are used to characterize device structure. A calibrated photodiode was used to measure the intensity of light through the laser using micro-channeled. Waveguide properties are characterized as a function of AIN film thickness and waveguide geometry. Results of a precise method in fabricating a prototype microfluidic waveguide system for nano-drug delivery will be presented.

Y.7.18 MICRO AND NANO FABRICATING LIPID PATTERNS USING A POLYMER BASED WET LIFT-OFF. Reid N. Orth, Dept of Biomedical Engineering, Bojan Ilic, Harold G. Craighead, Dept of Applied and Engineering Physics, Ithaca, NY.

Lipid molecules were immobilized on the surface of silicon using a Parylene lift-off technique. Large unilamellar 1-palmitoyl 2-oleyl phosphatidylcholine lipid vesicles were found to bind on the native oxide surface of silicon. Vesicles were fabricated from tetrahydrofuran and tetra-ethyl-ortho-silicate etching were used to pattern a Parylene coated surface reliably to sub 4 μm features, which was subsequently coated with a lipid bilayer. The polymer is peeled away in deionized water from the substrate leaving the lipid bilayer. The Parylene lift-off technique was applied to a silicon wafer, and Parylene lift-off technique was applied to the micro-contact printing on silicon. Patterning was performed using different lipid conjugated biomolecules (polypeithylene glycol (PEG), biotin, fluorescent dyes, and DNA oligomers.

Y.7.19 PATTERNED NANOPARTICLE ASSEMBLY AS NOVEL CHEMICAL AND BIOLOGICAL PLATFORMS. Mathew M. Mow, Jia Liu, Li Han, Chunxin Zhong, Dept of Chemistry, State University of New York at Binghamton, Binghamton, NY.

The ability to assemble nanoparticles with controlled size, shape, and surface properties and subsequently to probe the nanostructure is crucial for exploring nanoscale biomimetic and biological functional properties. In this presentation, we will describe a novel approach to nanoparticle assembly as micro-patterned platform. Recent findings of scanning force microscopic investigation of biomimetic functional properties as such a platform of the nanoparticle assemblies will be discussed. Highly monodispersed nanocrystals generated by thermally-activated protolysis or functionalized nanoparticles are utilized to assemble nanoparticle thin film architectures. Nanomaterials import biomimetic ion-channeling properties at the macrostructure/liquid interface under pH tuning. By probing nanoparticle assembly on surfaces as a platform with micro-sized addresses, the microscopic results of both friction force and topography reveal intriguing morphological changes associated with the nanostructured biomimetic activity and antibody-antigen interactions. Both qualitative and quantitative data about the ion and solvent fluxes in and out of the nanostructured membrane in solution are acquired, which allow us to gain insights into the detailed interfacial structures and processes. The results will be discussed for delineating the interfacial molecular interaction and the nanostructured biomimetic and biological functions.

Y.7.20 MANIPULATION OF DNA VIA ATOMIC FORCE MICROSCOPY. J. Bentz, D. Lagnosty, S.D. Gillmor, K. Mcklin, S. Limbach, D. van der Weide, and M.G. Lagally, University of Wisconsin-Madison, Madison, WI.

Scanned probe microscopy techniques have shown themselves to be extremely versatile, extending beyond microscopy to include lithography and other novel applications in which a probe is mechanically scanned with nanometer resolution is desired. Dip-pen lithography, using the AFM tip in a manner similar to a quill pen, shows promise as a novel method to write with alkane thiol molecules and as other organic solvents onto surfaces on the nanometer scale. We have scanned a pattern of AFM tip with a functionally modified nanomanipulator tip to move DNA on surfaces, placing it at desired locations to attempt to create an array with nanoscopic amounts of material. Nanotube AFM tips have the advantage of a high aspect ratio and can image a trench or channel with a higher degree of atomic resolution than traditional AFM tip. A nanotube tip can deposit solvent or other material in
such a 3D topology. We have chosen to work with DNA, as it is a useful biological molecule, although expansion to other molecules is foreseeable. In a huminically controlled environment, a small droplet of condensed DNA solution is deposited on a mica surface. A functionalyzed nanotube affixed to an AFM tip is subsequently immersed in the solution, and the chemical attraction aids in the transfer of DNA and solvent to the nanotube. When the tip is in contact with solvent, we can deposit solvent and DNA, like ink in a pen, in bundles of 50 nm in diameter, at specific locations on the mica surface. We discuss the difficulties and the promise of this technique. Supported by NSF.


Y7.21
CONTROLLED DEHYBRIDIZATION OF DNA Oligonucleotides by Induction Heating of Covalently Linked Au Nucleotides Konstantin Komorowski, Schaffler, Media Lab, Jiaqing Shi, Center for Biomedical Engineering, Shangqing Zhang, Center for Biomedical Engineering, Jay Schwartz, Engenies; Joseph M. Jacobson, Media Lab, MIT, Cambridge, MA.

The authors present experimental results on controllable dehybridization of DNA oligonucleotides by induction heating. The oligos are covalently linked to gold nanocrystals which can be induced to heat. By placing the sample in an alternating magnetic field, eddy currents are induced in the nanocrystals. Because the field and the induced eddy currents are alternating, the nanocrystals heat rapidly. Oligonucleotides covalently linked to the nanocrystals can be heated to dehybridize from their complements. Induction heating can rapidly dehybridize DNA oligos, on the timescale of a few seconds. The authors show results that the induction heating is not global but selective, meaning that only one has the ability to heat oligos that are gold labeled but not unlabeled. They are presented in the same solution. Applications of this technique in biomedicine and computing will be discussed.

SESSION Y8/AA9 JOINT SESSION NANOPATTERING OF ASSEMBLED SYSTEMS Chairs: Marie Angelopoulos and Elizabeth A. Dobisz Thursday Morning, November 29, 2001

8:45 AM *Y8.3/AA9.3
INTRODUCTION TO ALKANETHIOLS IN NANOPATTERNING P.E. Sheehan, L.J. Whitman, Naval Research Laboratory, Washington, DC.

The patterning of alkanethiols has become a cornerstone in the burgeoning field of nanotechnology. Several patterning techniques have been developed, and the more popular of which include stamping using polymeric masters, known as microcontact printing (mCP) and, more recently, the deposition of the thiols using an AFM tip, known as Dip Pen Nanolithography (DPN). Importantly, in both techniques, diffusion of the thiol away from the contact area fundamentally limits the spatial resolution obtained. Obtaining the highest resolution possible in these techniques will require control of the rate and nature of thiol diffusion. To address this need, the ratio of octadecanethiol spots deposited via DPN was studied as a function of tip surface contact time and relative humidity. The increase in spot size with time was well described by a two-dimensional radial diffusion from a constant source of finite radius. Fits using this formula revealed a diffusion constant of approximately 250 nm²/s with little dependence on humidity. Analysis of published images showing the spread of hexadecanethiol on gold after microcontact printing leads to comparable diffusion constants. Significantly, these values are four orders of magnitude smaller than that expected for diffusion through a bulk fluid such as water. Finally, the role of the water meniscus in DPN will be discussed.

9:15 AM Y8.2/AA9.2
DIRECTED ASSEMBLY OF ONE-DIMENSIONAL NANO- STRUCTURES INTO INTEGRATED DEVICE ARRAYS Yu Huang, Charles M. Lieber, Harvard Univ., Dept. of Chemistry, Cambridge, MA.

There have been increasing interest in using one-dimensional nanostructures as building blocks for bottom-up assembly of nanoscale electronics because they may serve both as wiring and critical device elements in future device architecture. A number of electronic and optoelectronic devices have been demonstrated using nanowires as the building blocks so far. The major challenge has been to organize one-dimensional nanostructures into integrated device arrays. Here we present a rational approach based on fluids for the hierarchical assembly of one-dimensional nanostructures into well-defined functional networks. We show that nanowires can be assembled into parallel arrays with control of the average separation, and by combining fluidic alignment with nanowire patterning technique, it is also possible to introduce periodicity. In addition, complex crossed nanowire arrays can be prepared using layer-by-layer assembly with different flow directions for sequential steps. Transport studies show that the crossed nanowire arrays form networks, with individually addressable device function at each cross point. Lastly we will show that these parallel and orthogonal nanowire arrays can be used to construct integrated logic and memory device arrays.

9:30 AM Y8.3/AA9.3
SELF-ASSEMBLY PATTERNING OF COBALT DISILICIDE NANOSTRUCTURES USING LOCAL STRESS EFFECTS P. Khat, Q. Zhao, S. Wissel, S. Lens, and S. Moel, Forschungszentrum Jülich, Institut für Schichten und Grenzflächen [16G-IT], Jülich, GERMANY.

We show a new self-assembly patterning method for generating epitaxial cobalt disilicide nanostructures with dimensions down to 30 nm. This technique is based on anisotropic diffusion of Co/Si atoms in a strain field during rapid thermal processing. The strain field is generated along the edges of a mask consisting of 20 nm SiO₂ and approximately 300 nm Si₃N₄. This mask, which is similar to that of the well known LOCOS process, is patterned with conventional optical lithography and dry etching. Single-crystalline CoSi₂ layers grown by molecular beam epitaxy (MBE) on Si(100) or ultrathin silicon on insulator (SOI) substrates were patterned using this technique. During rapid thermal oxidation (RTO) of the masked silicide structure, a well defined separation of the silicide layer forms along the edge of the mask. These highly uniform gaps are as narrow as 40 nm. Combining this process with selective underetching of the SOI underneath the mask and/or silicide/silicon etching delivers highly uniform CoSi₂ nanowires with diameters down to 50 nm. In addition, two parallel nanowires with a distance of 3 nm were achieved. Overlapping stress fields of two mask edges were used to generate 80 nm wires. The same masking technique was used to create nanocaps during the silicide reaction forming epitaxial CoSi₂ in a strained oxide mediated epitaxy process. Here, the mask was deposited on a Co/Hf/SiO₂/Si structure. Subsequent rapid thermal annealing in forming gas (90% N₂, 10% H₂) leads to the formation of epitaxial CoSi₂ with a gap of approximately 100 nm along the edge of the mask. Simulations to estimate the stress profiles generated by the nickel hard mask using an AFM process simulation tool were performed and are in agreement with our patterning results. The generated structures were used as building blocks for the fabrication of nanoscale MOSFET devices.

9:45 AM Y8.4/AA9.4
INTELLIGENT POLYLECTROLYTE MULTILAYERS pH-RESPONSIVE DEPOSITION/REMOVAL OF THE MULTILAYER THIN FILMS AND THEIR MICRO-PATTERNING Sung Yun Yang, Michael F. Rubner, Massachusetts Institute of Technology, Dept. of M&SE, Cambridge, MA.

Recently, we have succeeded to build up multilayer films via a layer-by-layer (LbL) technique using hydrogen bonding. Polycrylamide (PAAm) was used as a non-ionizable polymer, poly(acrylic acid) (PAA) and poly(methacrylic acid) (PMA) were used as hydrogen-bonding partners. Multilayers were subsequently patterned by alternate deposition of films or silicon substrates into the dilute polymer solutions at pH 3. At this pH, most of the carboxylic acid groups exist in the non-ionized form, and are available for hydrogen bonds. The key of this experiment was controlling the pH of all solutions including the solutions used in the rinsing steps in the process. The multilayers are stable at low pH and dissolved at high pH. Importantly, at physiological condition (pH 7.2, phosphate buffered solution) these multilayers dissolve into the buffer solution within a minute. This pH change breaks hydrogen bonds between layers by generating negative charges in the ionizable polymer (PAA and PMA). Thermal treatment of these multilayers, which results in a partial cyclod anhydride formation between carboxyl groups in the polymer chains, gives the multilayer a good stability at high pH. FTIR spectroscopy experiments confirm there is a high level of hydrogen bonding between amide and acid groups. Ellipsometry and quartz crystal microbalance (QCM) data of the multilayers with different molecular weights of PAAm were taken. In addition, cell adhesion to these multilayers was studied. Using the pH-dependent stability and UV-curable ability of the multilayers, we have succeeded in micro-patterning the films by inkjet printing and photolithography. This type of multilayer system has a great potential in nanopatterned materials as well as in drug delivery.

10:30 AM Y8.5/AA9.5
NANOCONTACT PRINTING OF PATTERNED SUBMICRON FEATURES OF SELF-ASSEMBLED THIOL DERIVATIZED POLYMERS John F. Rabolt, Mei-Wei Teng, Jianhong Li, University of Delaware, Dept. of Materials Science and Engineering, Newark, DE.
Microcontact and nanocontact printing have been used to produce patterned polymer films on monolayers (SAMs) and self-assembled monolayers (SAMs) on a variety of substrates such as gold, silver, or glass. In this technique, an elastomeric stamp, fabricated from poly(dimethylsiloxane) (PDMS) using a polymer master is wetted with an ink and used in the deposition of a thin polymer film. The polymer is then transferred conformal contact to a substrate. In this talk, we will describe the formation of PDMS stamps from commercially available ready-to-use compact disks (master) that have already been poly(dimethylsiloxane) (PDMS), and self-assembled monolayers (SAMs) were then deposited on gold surfaces using submicron contact printing and microcontact molding techniques. Utilizing an atomic force microscope (AFM), these patterned surfaces were characterized and analyzed to determine the dimensional and aspect ratio of the features produced. Polycrystalline PtTiR measurements were made on the 5.5 nm thin transferred polymer films in order to assess the extent of polymer orientation induced by the stamping process.

10:45 AM Y8.6/A9.6
NANOPATTERNING 2D METALLIC SURFACES BY SOFT LITHOGRAPHY
Mohammed S. Teiger, German Salinas-Alvarez, Do-Kyung Kim, Martin Mikkelsen, M. Scotti Mohammed, Royal Institute of Technology, Dept of Materials Science and Engineering, Materials Chemistry Div, Stockholm, SWEDEN.

The fabrication of large areas of structured surfaces with feature sizes in the nanometer regime is still a challenge. Modern approaches to structure surfaces in sub-micrometer range involve the use of lithographic techniques, which have limitations regarding the minimum feature size. Nanoscale structures are made by improved methods, in which microcontact printing (μCP) uses an ink patterned stamp to direct chemical reactions between molecules from the ink and the surface of a substrate. In this study, we report on the development of patterned chemistries where the ink used on the surface of the stamp is made of alkylamid solutions. Si was used as substrate on which self-assembled monolayer of nanoparticles was formed at the contact regions. The stamps for μCP are prepared from poly(dimethylsiloxane) (PDMS) by polymerizing on a master defined by self-assembled colloidal SiO2 spheres. The regions of contact subsequently used for deposition of metal nanoparticles resulting in 2D patterned metallic surfaces. By changing the size of nanoscale features on the master, it is possible to control the size and distance between contact points, i.e. metal deposited points, on the substrate. The chemical and physical properties of the system are investigated where the printed substrates were characterized by SEM and atomic force microscopy (AFM) technique and deposited particles were characterized by XRD.

11:00 AM Y8.7/A9.7
FIELD INDUCED PATTERNING OF MECHANICALLY CONFINED POLYMER FILMS
David G. Budnail, Department of Materials, University of Oxford, UNITED KINGDOM

At elevated temperatures polymer films on a non-wetting solid surface form quasi-periodic patterns resulting from film rupture and dewetting [1]. This behaviour can be prevented by mechanically confining the film by a capping layer of, for instance SiOx, to produce a completely flat surface morphology [2]. This paper presents results of our recent studies on the morphological changes which occur to such mechanically confined films when an electric field is applied normal to the film thickness. An electric field applied across a polymer film with a free surface is found to produce structures which are either columnar or replace the topography of the electrode [3]. By capping the polymer film with a thin metal layer, we produce very different structures. The effect of applying an electric field to these capped polymer films during annealing or elevated temperatures for a few minutes is to produce lateral morphologies which display both micrometric, highly linear regions as well as areas which are totally isotropic. The effect the polymer film and capping layer thickness and field strength on the resulting structures will be presented.


11:15 AM Y8.8/A9.8
PLANAR MOLECULAR AND MACROMOLECULAR GRADIENTS: PREPARATION AND PROPERTIES
Jan Geuser, Kirill Efremenko, Tao Wu, Dept of Chemical Engineering, NC State University, Raleigh, NC.

Deposition of self-assembled monolayers (SAMs) offers one of the highest quality routes of systematically tuning the surface properties of materials: by controlling the chemical composition of the terminal group, the length, and microstructure of the SAM molecule, the chemical and physical properties, including wetting, adhesion, friction, and bioactivity, can be successfully tailored. While early studies concentrated mainly on patterned surfaces with homogeneous SAMs, recent advances in the field allowed for creating SAMs with two-dimensional chemical patterns. In particular, the microcontact printing (μCP) technique has proven to be a convenient method for producing different SAMs. While μCP is useful for decorating materials substrates with a variety of motif shapes and dimensions, it always produces sharp boundaries between the distinct chemical substrate regions. However, for applications requiring the wetting properties of the substrate to change gradually over a certain region in space. This situation can be accomplished by producing surfaces with a gradually varying chemistry along their length. In these so-called gradient substrates, the gradient in surface energy enables for a smooth transition in physical properties, most notably the wettability. Such gradient surfaces can be particularly useful to study interactions in biological systems, as the influence of the entire wetting spectrum upon protein adsorption or cell interactions can be investigated in one single experiment. In our presentation we will discuss several methodologies of preparing planar molecular and macromolecular gradients on substrates. We will show that the gradient properties (including the wettability change and chain orientation) can be elucidated by a combination of several complementary experimental tools, including NEXAFS, static and dynamic contact angle measurement, spectroscopic ellipsometry, and FTIR. Moreover, we will demonstrate that the gradient properties (including steepness, position of diffusing front, and wettability) can be finely-tuned by forming the gradients on a flexible (and thus deformable) substrate, such as an elastomeric network.

11:30 AM Y8.9/A9.9
SOFT CONDENSED MATTER NANO- AND MESOSCOPIC PATTERNS ON SEMICONDUCTOR SURFACES.
V. Smalyuk, V. Yurchenko, I. Kuts, S. Hennrich, Stony Brook, NY.

The most striking property of soft condensed matter is the ability to selforganize - to create spontaneously oriented or periodic states on nano- and mesoscopic scale [1]. A novel and simple approach of self-organized fabrication of two dimensional mesoscopic networks with the feature size down to 50 nm has been developed. The technique is based on the self-organized patternning in a thin layer of complex liquid (solution) in the presence of humid atmosphere. Two dimensional mesoscopic honeycomb-shaped carbon structures were produced by high temperature annealing of novel alkylidene compounds [2]. The polymer network was also utilized as a mask for further reactive ion etching of surfaces with epilayer of GaN [3,4] and GaNs/AlGAs doped heterostructures [5]. These structures can be considered as regular arrays of mesoscopic or 2-D photonic band gap crystals. We have used diblock copolymer system, self-assembled with L-B technique, to produce nano-patterns. These structures were used as templates for introducing metal nanoparticles on semiconductor surfaces by reactive ion etching for magnetic storage systems [6] and DNA separation on a flat surface [7] devices. DNA molecules positioning on Si surface by simple physical alignment process has been developed. The capillary forces applied by the recessing front of the evaporation drop carrying DNA molecule were used to align them perpendicularly to the direction of drying front. This alignment was used as a precise DNA molecules loading technique on Si surface in a new method of DNA separation [8]. We determined the resolution related to loading width of the thickness of the line, which was approximately equal to the length of the stretched DNA molecules.

We demonstrate the application of nickel nanowire arrays for perpendicular magnetic storage media with areal densities beyond the perpendicular magnetic limit at room temperature. Highly ordered arrays of Ni nanowires, which are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263]. Highly ordered arrays of Ni nanowire arrays are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263]. Highly ordered arrays of Ni nanowires, which are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263]. Highly ordered arrays of Ni nanowires, which are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263]. Highly ordered arrays of Ni nanowires, which are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263]. Highly ordered arrays of Ni nanowires, which are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263]. Highly ordered arrays of Ni nanowires, which are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263]. Highly ordered arrays of Ni nanowires, which are used as templates for the fabrication of magnetic nanowire arrays, these well-defined templates are based on an approach by Massada and Fukuda [1995, 263].
amorphous carbon support. In particular, the high-temperature sintered particles are found to form patches of hexagonal close packed pattern via self-assembly on the substrate. Particles within such a pattern do not touch one another but are separated by some 1.5 nm, though these particles do not wear any coating. The observed inter-particle separation is ascribed to the formation of carbon walls on the underlying amorphous carbon film. In case of the HP-sintered particles, the irregular non-equilibrium morphology seems to impede the pattern formation.

4:00 PM Y9.6
Magnetic Properties of Three-Dimensional Periodic Nanostructures. L. Sun, Department of Materials Science and Engineering, C.L. Chien, Department of Physics and Astronomy, P.C. Searson, Department of Materials Science and Engineering, The Johns Hopkins University, MD.

Nanoporous magnetic structures with three dimensional periodicity have been fabricated by electrodeposition into self-assembled colloidal templates. Although ordered structures can be fabricated by conventional thin film processing, sequential deposition and lithography over many layers is time consuming. In contrast, the assembly of colloidal crystals to form ordered structures in many layers thick can be achieved in a single processing step. In this work, hexagonal microspheres are self-assembled to form periodic, closed packed templates. Three-dimensional ferromagnetic structures with nanoscale scale periodic features are formed in these templates by electrodeposition. The magnetic properties of these 3D nanostructures are reported.

4:15 PM Y9.7
High-Density Magnetic Dot and Anti-Dot Array Fabrication Via Nanosphere Physical Masks. G.C. Spindler, Paul Currie, Brad Andrew, Illinois Weskym Univ, Dept of Physics, Bloomington, IL, J.E. Ellenbogen, Univ of Illinois, Dept of Physics, Urbana, IL.

We discuss non-lithographic means of controlling the assembly of nanoparticles on a substrate. Following the work of Xin's group [1], we describe the construction of uniform microfluidic cells which may be used to encourage a collection of monodisperse, mesoscale particles to form large-scale, ordered colloidal crystals. In our work, cells are designed to form monolayers and bilayers. We discuss the use of these monolayers and bilayers as physical masks during the deposition of metals, in order to produce high density, ordered dot arrays [2]. We also introduce the use of such masks in the production of anti-dot arrays. That is, once assembled, the colloidal monolayers or bilayers can serve as a physical mask, selectively protecting areas of the underlying substrate from either physical vapor deposition or from a reactive plasma. Because the clear, line-of-sight channels between the masking particles are much smaller than the particles themselves, extremely fine features can be transferred to the substrate. This novel technique for high-density nanopatterning is inexpensive, can work on curved surfaces, and over extremely large areas. We discuss details of the fabrication, the tunability of feature sizes, and a variety of applications.


4:30 PM Y9.8

The smallest lateral feature on commercial microprocessors is currently 150 nm, while the distance between binding sites on a human antibody is ~10 nm. Nanofabrication at biologically important length scales is expected to remain beyond the capability of commercial lithography for the foreseeable future. A new method for the fabrication of periodic arrays of surface features with controlled spacing of 2-100 nm will be described in this paper. Our approach is based on the two-dimensionally periodic screw dislocation array that occurs at the interface between two single crystal substrates twist-bonded at a misorientation angle θ to form a bicrystal. The desired periodic structure is brought to the surface by a dislocation etch. The spacing, d, between the dislocations (and the features of the surface structure) is related to θ by Frank's rule, d = b/2nf(θ/2), where b is the dislocation Burgers vector. The feasibility of this approach will be demonstrated. A Si bicrystal was formed by twist-bonding a Si (100) wafer to a 100 nm thick Si (100) single crystal film that is part of a commercial silicon-on-insulator (SOI) wafer. After removal of the Si handle crystal and thin silicon dioxide film, the upper thin crystal of the bicrystal was etched. Atomic force microscopy showed periodic surface features with spacing of 38 nm, in good agreement with the chosen θ. Periodic spacings between 100 nm and 2 nm can be generated by varying θ between 0.2 degree and 10 degree. Such nanoperiodic structures have a variety of electronic, magnetic storage and biological applications.