SYMPOSIUM J

Advanced Materials and Techniques for Nanolithography

November 28 – December 1, 1999

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* Invited paper

TUTORIAL

FTJ: ADVANCED RESISTS FOR MICRO- AND NANOLITHOGRAPHY
Sunday, November 28, 1999
2:00 - 5:00 p.m.
Room 204 (H)

This tutorial will begin with a brief introduction to lithographies in microelectronics and the need for advanced polymer resists. A brief historical outline of resist materials will then be given, with the focus on the following topics:

- The technical requirements that have driven the evolution of resist materials
- The range of resist chemistries that have been used over time
- Key resist advances that have been made in response to new exposure technology/application requirements
- Materials up to and including DNQ-novolac resists

A section on modern resists based on chemical amplification will cover:

- Motivations for developing CA resists
- Mechanisms/modes of operation
- Explanatory examples of CA resist chemistries for 248 nm lithography
- Chemistry/properties of materials in use today in the manufacturing setting
- How and why CA resist materials are evolving for near-term future use in 193 nm lithography

The final section on next-generation lithographies will discuss at an introductory level the top candidates for NGL exposure technologies; the unique resist requirements of each of these different NGL technologies; and potential limits of extendibility of resist materials due to factors such as photoproduct diffusion, line edge roughness, and thinner films vs. defects and etch resistance.

Instructors:
William D. Hinsberg, IBM Almaden Research Center
Kenneth Gonsalves, University of Connecticut
Lhadi Merhari, CERAMEC France

SESSION J1: ADVANCES IN PHOTO AND X-RAY LITHOGRAPHIES; ISSUES FOR MOLECULAR SCALE ELECTRONICS
Chairs: Kenneth E. Gonsalves and Lhadi Merhari
Monday Morning, November 29, 1999
Boston College (M)

8:30 AM *J1.1
EXTREME ULTRAVIOLET LITHOGRAPHY AND THE MATERIALS CHALLENGE. Sheila Vaidya, Don Sweeney, Lawrence Livermore National Laboratory, Information Science and Technology Program, Livermore, CA; Rick Stulen, Sandia National Laboratory, EUVL, Livermore, CA; David Attwood, Lawrence Berkeley National Laboratory, Center for X-Ray Optics, Berkeley, CA.

Extreme Ultraviolet Lithography (EUVL) has emerged as one of the leading successors to optics for sub 0.1 μm IC fabrication. Its strongest attribute is the potential to scale to a much finer resolution at high throughput. As such, this approach could satisfy the lithography requirements for Si intergrated circuits down to fundamental device limits. In the United States, Lawrence Livermore, Sandia, and Lawrence Berkeley Laboratories are participating in an industry funded research effort to evolve EUV technology and build a prototype camera for lithographic exposure. This effort has driven the state-of-the-art in optics fabrication and coatings, in mask making, as well as in the use of thin photoresists for 50nm imaging. This talk will review some of the major advances in aspheric optics fabrication, the attendant metrology innovations, and the multilayer coating technology, which have enabled the design of a high throughput, all-reflective imaging system with lithographic quality imaging behavior. Multilayer coated aspheric optics have necessitated the evolution of deposition techniques which provide stress control and better than 0.1% thickness uniformity across 8 substrates; the reflective mask imposes additional demands on substrate quality, multilayer interface perfection and mask defect density. These requirements are well on the way to being met through model-based deposition control and advanced diagnostics. In the photoresist arena, conventional DUV materials are showing significant promise with regards to line edge roughness and resolution in bilayer/trilayer configurations. These results will be reviewed and the challenges remaining highlighted.

9:00 AM J1.2
DEFECT EVOLUTION IN MULTILAYER-COATED RETICLES FOR EUV LITHOGRAPHY. P.B. Mirkarimi, D.G. Stearns, S.L. Baker, P.A. Kearney, S.C. Burkhart and D.W. Sweeney, Lawrence Livermore National Laboratory, Information Science and Technology Program, Livermore, CA.

Extreme ultraviolet lithography (EUVL) is one of the leading candidates for synthesizing integrated circuits with critical dimensions of less than 70 nm. EUVL reticles are fabricated by depositing multilayer reflective coatings such as Mo/Si on superpolished substrates. The reticles must be nearly defect-free in the sense that there can not be localized structural imperfections in the coating that perturb the reflected radiation field sufficiently to print at the wafer. Consequently it is important to understand and control the evolution of defects nucleated by small particle contaminants at the substrate/multilayer film interface. In order to investigate and quantify the effect of particulates on the film growth, we have deposited low particulate ion beam sputtered Mo/Si multilayer films on substrates with particles of known sizes, ranging from 20 to 80 nm in diameter. We have used atomic force microscopy (AFM) and transmission electron microscopy (TEM) to characterize the defects before and after coating. We compare our experimental results to recent theoretical studies of film growth based on a linear continuum model.

9:15 AM J1.3
SCANDIUM: A BRIGHT HOPE FOR MID EUV OPTICS? David D. Allred, R. Steven Turley, David Balogh, Spencer Olson, Matthew B. Squires, Douglas Markos, Alex Barabanov, and Jason Flint, Department of Physics and Astronomy, Brigham Young University, Provo, UT.

Below about 120 nm, there are no acceptable optical materials for lens or single surface mirrors which could be readily used for advanced lithography. The next band where there are well-researched multilayer mirrors (Mo/Si and Mo/Be) with high reflectance is from 11–14 nm. Normal incidence reflectances of above 70% have been reported. We would like to highlight the possibility of another band from 30–40 nm where highly reflective mirrors may be possible. A Russian group recently calculated that multilayer mirrors with high reflectivity ($R > 70\%$) for this range could be fabricated using scandium and silicon. They fabricated a Sc/Si mirror whose reflectance reached 50% at 37 nm[1]. We will report on materials science aspects of our work with scandium and other chemically active, but optically attractive, elements for multilayers for this range. We will address using the natural tarnish which forms on the mirror as an integral part of achieving the mirror's optical response, the use of barrier layers, and the design and characterization of aperiodic mirrors which perform several optical functions, including blocking some EUV wavelengths and acting as broadband reflector. Achieving reflectances above 50% could revolutionize optics in this range and provide a useful alternative to 11–14 nm for projection lithography. This may be important since compact sources of EUV light in the 30–40 nm range are more developed than for 11–14 nm. The material challenges include the strong effect that first row elements (especially C and O) have on altering the reflectances in this range, and the relatively high reactivity and diffusivity of many of the best optical materials in this range.
1. Yu. A. Uspenskii, et al., Optical Letters **23** (10), 771 (1998).

9:30 AM *J1.4
LITHOGRAPHIC MATERIALS TECHNOLOGIES: 193 NM IMAGING AND BEYOND. Elsa Reichmanis, Omkaram Nalamasu, Francis M. Houlihan, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; Allen H. Gabor, Mark O. Neisser, Murrae J. Bowden, Arch Chemicals, Inc., East Providence, RI.

Advances in microlithographic resist materials have been a key enabler of the unabated productivity gains in the microelectronics industry and are continuing to help push the ultimate limits of optical lithography. The challenges posed by the introduction of new optical technologies that use smaller wavelengths have been successfully met by the materials community through the design of chemically amplified resist technologies and 193 nm resist materials based on aliphatic polymers and dissolution inhibitors. With continued advances in resist materials, exposure systems and resolution

enhancement and mask technologies, optical lithography will be capable of patterning sub-one-tenth micron design rule devices in future fabs. This presentation will focus on the materials challenges that have been successfully met in the development of 193 nm lithographic materials technologies and begin to examine future directions.

10:30 AM *J1.5
IMAGE FORMATION IN HIGH-ENERGY LITHOGRAPHY: FRACTALS AND MATERIAL PROPERTIES. F. Cerrina, Electrical and Computer Engineering Department University of Wisconsin-Madison, Madison, WI.

The continuing decrease in device dimensions leads to the development of new patterning techniques. While there are several possible approaches, the most likely volume production techniques will be based on photon and electron projection schemes. In all cases, these lithography use particle of energy high enough to cause excitation of core levels, with subsequent emission of Auger electrons when the atom returns to the ground sate. Thus energy redistribution plays a vital role in exposing the photosensitive material. Interestingly enough, no detailed model explaining satisfactorily the process exists. Since line edge roughness (LER), i.e., resist linewidth fluctuations become more relevant as the dimension of the features decrease, it is becoming necessary to understand in detail the origin of these fluctuations. Most activity to date has concentrated on developing average values, and even Monte Carlo methods are based on continuum models for the energy loss. This models cannot predict detailed processes at the molecular level that are likely to be at the root of roughness and other statistical processes. In addition, the concept of LER itself must be explained, and in particular the meaning of "roughness". In order to quantify the LER more accurately, we have studied a quantification in terms of fractal analysis, and explored the confection between top roughness (TR, much easier to measure) and LER, concluding that the two are essentially the same. In this talk we will review the status of research on LER, and discuss its origin using both experimental results in Extreme Ultra Violet and X-ray Lithography, and show how the roughness is dependent not only on the physical process leading to image formation but also on the type of chemical reactions involved in the image storage, and in its development.

11:00 AM *J1.6
SOFT X-RAYS FOR DEEP SUB-100 NM LITHOGRAPHY, WITH AND WITHOUT MASKS. Henry I. Smith, Massachusetts Institute of Technology, Cambridge, MA.

The development of micro- and nanofabrication, their applications, and their dependent industries has progressed to a point where a bifurcation of technology development is occurring. On the one hand, the Semiconductor industry (at least in the USA) has decided to develop EUV and SCALPEL to meet its future needs. Even if the semiconductor industry is successful in this (which is by no means certain) such tools will not be useful in most other segments of industry and research that will employ nanolithography. As examples, MEMS, integrated optics, biological research, magnetic information storage, quantum-effect research, lithography on curved surfaces, and multiple applications not yet envisioned will not employ the lithography tools of the semiconductor industry, either because they are too expensive, insufficiently flexible, or lacking in accuracy and spatial-phase coherence. Of course, direct-write electron-beam lithography can meet many of these non-semiconductor-industry needs, but in other cases a technique of higher throughput or broader process-latitude is necessary. Our experience at MIT in applying low-cost proximity x-ray nanolithography to a wide variety of applications leads us to conclude that this technology can provide the alternative path of a bifurcation. A new version of x-ray nanolithography, zone-plate-array lithography (ZPAL), does not require a mask, and has the potential to reach the limits of the lithographic process with a maskless projection process. In this talk we will show results of deep-sub-100 nm lithography, and review the fundamental reasons why a lithography based on photons in the range 1 to 5 nm (i.e., x-rays) can provide: low capital costs, 20 nm resolution, high throughput, and sufficient flexibility to meet the needs of a variety of current and future industries.

11:30 AM *J1.7
MOLECULAR SCALE ELECTRONICS. CRITICAL NANOLITHOGRAPHY ISSUES OF SYNTHESIS AND ADDRESSING. James M. Tour, Rice University, Department of Chemistry and Center for Nanoscale Science and Technology, Houston, TX.

Synthetic organic routes to precisely defined conjugated macromolecules (molecular scale wires) will be described using solution and solid phase approaches. The molecular scale wires are based on poly(phenylene ethynylene)s and poly(thiophene ethynylene)s and they possess thiol, selenol, and tellurol end groups to function as molecular scale alligator clips. Ordering of these molecular scale wires on gold surfaces has been studies by ellipsometry, XPS, and grazing angle IR. Experimental approaches will be described for isolating some of these single molecules in alkane thiolate self-assembled monolayers and addressing them with an STM probe. Single molecule conductance has been measured using a mechanically controllable break junction. These experiments demonstrate single molecule conductivity and they are a prelude to the testing of single molecular scale devices. Several molecular based resonance tunneling diodes (RTD) have been demonstrated. Some other molecular scale structures that have been synthesized are wires with tunnel barriers, wires with quantum wells, three terminal systems that could act as molecular switches, four terminal systems that could be logic devices, and wires based on DNA/fullerene hybrids. Scenarios will be outlined wherein a single molecule could function as a logic device rather than the traditional use of multiple transistors. The devices have been modeled using density functional theory. Potential routes to molecular based CPUs will be outlined wherein electrostatic potentials are uses as the information-carrying packets. The enormous potential and obstacles of molecular scale electronic architectures will be discussed.

SESSION J2: ADVANCED RESISTS AND CHARACTERIZATION

Chairs: Kenneth E. Gonsalves and Paul F. Nealey
Monday Afternoon, November 29, 1999
Boston College (M)

1:45 PM *J2.1
RESIST MATERIALS AND NANOLITHOGRAPHY. Elizabeth A. Dobisz, Naval Research Laboratory, Electronics Science and Technology Division, Washington DC.

The work focuses on lithographic processes and materials for sub-50 nm lithography. The discussion will give a critical examination of the use of polymeric resists for nanolithography. This will be followed by a discussion of alternative resists, such as self assembled monolayers (SAMs). Polymers have radii of gyration ~5-50 nm, depending upon molecular weight, configuration, and solvent environment. The developer solvent can penetrate the remaining resist structure causing swelling. Developer induced resist swelling compromises the pattern integrity and the overall mechanical stability of the pattern. Furthermore, the current state-of-the-art chemically amplified resists (CARs) are composed of multi-components that can diffuse. Patterns are defined by e-beam lithography or STM lithography, which have a probe sizes less than 10 nm. Atomic force microscope and scanning electron microscope images provide complementary information on pattern formation. The results are compared to calculated image profiles. With carefully controlled process conditions, ~10 nm lines and 40 nm period gratings can be produced in some polymer resists. 20-25 nm lines can be produced in a CAR. Small molecule SAM resists have been proposed to circumvent the macromolecular resist issues and for applications requiring thin resists. A review of work at the Naval Research Laboratory on a metal binding SAM resists is given.

2:15 PM *J2.2
FACTORS CONTROLLING PATTERN FORMATION IN POLYMERIC RESISTS AT NANOSCALE DIMENSIONS.
W. Hinsberg, F. Houle, G. Wallraff, M. Sanchez, M. Morrison, J. Hoffnagle, Hiroshi Ito, Cattien Nguyen, C.E. Larson, P.J. Brock and G. Breyta, IBM Research Division, Almaden Research Center, San Jose, CA.

At minimum feature dimensions below 100 nm, the required dimensional tolerances for pattern formation in integrated circuit fabrication approach the length scales of the molecular components and processes typically found in a polymeric resist film. Photoacid diffusion and line-edge roughness are two key factors that influence dimensional control and determine the ultimate extendibility of chemically amplified photoresists to the fabrication of nanoscale devices. In this paper, newly developed experimental methods for quantifying these characteristics will be described and recent results will be summarized.

2:45 PM J2.3
DIFFUSION OF PHOTOACID GENERATORS IN THIN POLYMER FILMS. Qinghuang Lin, Marie Angelopoulos, IBM T. J. Watson Research Center, Yorktown Heights, NY; Narayan Sundarajan, Gina Weibel, Christopher K. Ober, Department of Materials Science and Engineering, Cornell University, Ithaca, NY.

Fundamental understanding of the diffusion of small molecules, such as photoacid generators (PAGs), photo-generated acids, base additives and solvents, is critical to the rational design of high performance resist materials. In this work, direct measurements of the diffusion of

two fluorinated PAGs in thin polymer films were conducted with Rutherford Backscattering Spectrometry (RBS) and Secondary Ion Mass Spectroscopy (SIMS). Diffusion of the PAGs from thin films of poly(methyl methacrylate) or a silicon-containing methacrylate copolymer into the underlying thermally cross-linked Novolak films on a silicon substrate has been investigated as a function of the Novolak cross-linking temperature. Both RBS and SIMS results showed that deposition of the PAG containing polymer films on top of the cross-linked Novolak film by spin coating results in an interphase with enriched PAG. Subsequent annealing of the film stack causes expansion of the interphase and diffusion of the PAG into the underlying Novolak film when Novolak is cross-linked at lower temperatures. On the other hand, there is no detectable diffusion of the PAG into Novolak when it is cross-linked at high temperatures. The effects of the PAG molecular size, the microstructure of the cross-linked Novolak films on the PAG diffusion will be discussed. The effects of the PAG diffusion on lithographic performance of a bilayer resist will also be presented.

3:30 PM *J2.4
RESIST MATERIALS PROVIDING SMALL LINE-EDGE ROUGHNESS. Hideo Namatsu, Toru Yamaguchi and Kenji Kurihara, NTT Basic Research Laboratories, Kanagawa, JAPAN.

In sub-100-nm lithography, accuracy of linewidth as well as resolution become important factors. This is because the amount of linewidth fluctuation cannot be disregarded as the linewidth decreases. The evaluation of the linewidth fluctuation has been reported as line-edge roughness (LER) by many researchers. However, so far there has been little discussion of the cause of, or how to reduce LER. To find a solution, we have been studying the factors yielding smaller LER by examining the properties of resist materials. In this paper, we report on the cause of LER in nanolithographic resists, and also on material approaches for reducing LER. Polymer aggregates, which are generally contained in resist films, cause LER. When the aggregates exist in the resist film, development rate becomes uneven. This is because the aggregates are not dissolved but extracted in the developer. The aggregates that remain at the pattern sidewall result in LER. Therefore, preventing the aggregate extraction leads to resist patterning free from LER. There are two approaches to reducing the influence of the aggregate extraction on LER. One is a technique of reducing the influence even if the extraction occurs. The other is suppressing the extraction itself. The former can be achieved by using a small aggregate resist. A typical example is hydrogen silsesquioxane resist. The effectiveness of this resist in reducing LER has been confirmed by improving the properties of single electron transistors. The latter is obtained by reducing the difference in the development rate between the aggregates and the surroundings. We have achieved a resist with a small difference in the development rate by cross-linking the aggregates.

4:00 PM J2.5
OPTICAL CHARACTERIZATION AND PROCESS CONTROL OF TOP SURFACE IMAGING RESIST. Ying-Ying Luo, KLA-Tencor Corporation, Film and Surface Technology Division, Milpitas, CA; Craig Stauffer, GENESIS, Santa Clara, CA; Carlos Ygartua, Dinh Chu and Clive Hayzelden, KLA-Tencor Corporation.

The use of selectively silylated resists to facilitate top surface imaging (TSI) offers the potential for nanoscale lithography using both deep ultra violet (DUV) illumination and electron beam techniques. In this process, an exposure-generated crosslinking prevents silicon incorporation from silylating agents. In the non-crosslinked regions, silylation agents react with OH groups in the resist to form silicon-oxygen bonds. During subsequent dry development in an oxygen plasma, the incorporated silicon attracts oxygen to form silicon dioxide, protecting the resist underneath. The adjacent un-silylated resist erodes (develops) anisotropically 25-100 times faster than the silylation-protected resist. The key to this process is the chemical formation of a silylated region at the top of the resist. A challenge associated with the silylation process, however, is lateral swelling of the silylated layer, which can lead to difficult dimensional control. The amount of swelling depends on the amount of incorporated silicon. Therefore, the uniformity and repeatability of the silylation process must be controlled. This paper will describe how spectroscopic ellipsometry (SE) has been used to characterize and monitor the resist silylation process in a non-destructive manner. The simultaneous characterization of the thicknesses and optical properties of a series of silylated resists will be presented. Optical metrology of the thickness of the silylated resists will be correlated with SEM cross-sectional analyses, and process uniformity will be quantified using 49-site wafer maps.

4:15 PM J2.6
A NEW PURGED UV SPECTROSCOPIC ELLIPSOMETER TO CHARACTERIZE 157NM NANOLITHOGRAPHIC MATERIALS. Pierre Boher, Jean Philippe Piel, Patrick Evrard and Jean Louis Stehle, SOPRA S.A., Bois Colombes, FRANCE.

Spectroscopic ellipsometry has long been recognized as the technique of choice to characterize thin films and multilayers. In 1983, SOPRA has developed the first commercial spectroscopic ellipsometers for research and development. Since this date, the wavelength range has been extended from visible to near infrared (2μm), and far infrared up to 18μm. For 193nm microlithography, deep UV option down to 190nm has also been developed and sold more recently. Instrumentation for the next generation of UV lithography at 157nm requires special optical setup since oxygen and water are extremely absorbing below 190nm. The new system works into a purged glove box to reduce the oxygen and water contamination in the part per million range. The optical setup includes a premonochromator in the polariser arm to avoid resist photobleaching. The beam size on the sample is around 5mm diameter and the wavelength resolution better than 150 at 157nm. The system works in rotating analyser configuration to minimize the parasitic polarisations. A compensator can be used to enhance accuracy on layers deposited on transparent substrates. Ellipsometric and photometric measurement versus wavelength and angle can be performed. The proposed paper will present in details the new system with some first experimental results in the field of nanolithography.

4:30 PM J2.7
SYSTEMATIC STUDIES OF FULLERENE DERIVATIVE ELECTRON BEAM RESISTS. A.P.G. Robinson, R.E. Palmer, Nanoscale Physics Research Laboratory, School of Physics and Astronomy, The University of Birmingham, Birmingham, UNITED KINGDOM; T. Tada, T. Kanayama, Joint Research Center for Atom Technology, National Institute for Advanced Interdisciplinary Research, Tsukuba, JAPAN; E.J. Shelley, D. Philp, J.A. Preece, School of Chemistry, The University of Birmingham, Birmingham, UNITED KINGDOM.

We report systematic studies of the response of C_{60} derivatives to electron beam irradiation. Films of thirteen different mono, tris and tetra adduct methanofullerene C_{60} derivatives were produced by spin coating on hydrogen terminated silicon substrates. Exposure of the films to a 20 keV electron beam substantially altered the dissolution rate of the derivative films in organic solvents such as monochlorobenzene. All of the derivatives exhibited negative tone resist behaviour with sensitivities between ~ 8.5 (10^{-4} and ~ 4 (10^{-3} C/cm^2, much higher than that of C_{60}. Features with widths of ~ 20 nm were produced using these compounds, and the etch ratios of the compounds were found to be more than twice those of a standard novolac based resist (SAL601).

4:45 PM J2.8
EXTENDING THE POSSIBILITIES OF NEAR-FIELD SCANNING OPTICAL MICROSCOPY FOR SIMULTANEOUS TOPOGRAPHICAL AND CHEMICAL FORCE IMAGING. Noemi Nagy, M. Cynthia Goh, University of Toronto, Department of Chemistry, Toronto, ON, CANADA.

Near-field scanning optical microscopy (NSOM) is an innovative new form of surface microscopy which can be used to obtain both topographical and spectroscopic information about a surface. The most important component of this instrument is the scanning probe tip which is used as both a topographical probe and an optical probe for spectroscopic measurements. In this presentation, we discuss the production of a novel fiber optic probe for use in an NSOM. The probe consists of a bent, tapered silicon dioxide optical fiber. We have determined the rates of selective wet chemical etching of germanium dioxide doped pure silica optical fibers and used this information to optimse the probe etching process. The systematic approach for the development and testing of such probes will be presented. We have performed characterisation of the optical probes using surfaces prepared by the technique of microcontact printing. Phase and friction images of these surfaces were obtained using both standard atomic force microscopy tips and the optical fiber probe. The new optical probe was capable of distinguishing between different chemical regions on the patterned surface. Methods for chemical modification of the optical probe and its sensitivity as a cantilever to image chemically different regions, in both a controlled gas atmosphere and under liquid will be discussed, as well as the potential for using NSOM to perform simultaneous topographic, spectroscopic and chemical force imaging.

SESSION J3: ADVANCES IN ELECTRON BEAM, ION BEAM AND SOFT LITHOGRAPHIES

Chairs: Elizabeth A. Dobisz and Lhadi Merhari
Tuesday Morning, November 30, 1999
Boston College (M)

8:30 AM *J3.1
SCALPEL PROJECTION ELECTRON BEAM LITHOGRAPHY.

Lloyd R. Harriott, Bell Labs, Lucent Technologies, Murray Hill, NJ.

One of the leading candidates for next generation lithography is SCALPEL (SCattering with Angular Limitation Projection Electron-beam Lithography) SCALPEL is a reduction image projection technique which uses 100 keV electrons to produce images by scattering contrast. The use of electrons circumvents diffraction which limits the performance of optical lithography. We have a comprehensive program to develop SCALPEL as a lithography technology. Our efforts are in the areas of mask technology, resist and processing, as well as exposure tool technology. In our mask program we have developed masks using a small-field 100 mm diameter format. Both mask blank fabrication and mask patterning activities have been transferred to commercial suppliers for this format. We are developing a full-field mask technology based on a 200 mm diameter format which will be transferred to commercial vendors in the near future. Our activities in resist and processing for SCALPEL have been largely focused on using resist platforms developed for chemically amplified deep-uv (DUV) lithography at 248 nm and 193 nm.. We have demonstrated the feasibility of SCALPEL technology on our Proof-of-Lithography (POL) exposure tool and have reported on it in the past. We are now designing a high throughput exposure tool which implements beam scanning and seam blending to simultaneously achieve high throughput and meet critical dimension (CD) control requirements for the 100 nm generation. Our throughput models show that we will be able to expose 24 300 mm wafers per hour with this design and that with modest evolution, be able to maintain that throughput through at least the 50 nm generation. This design will be the basis for commercial introduction of SCALPEL technology. In this talk, I will describe our SCALPEL program and discuss its introduction as a disruptive technology. This work was supported in part by DARPA and SEMATECH. SCALPEL is a registered trademark of Lucent Technologies.

9:00 AM *J3.2
A REVIEW OF ELECTRON BEAM LITHOGRAPHY: HISTORY AND STATE OF THE ART. Dustin W. Carr, Richard C. Tiberio, Cornell Nanofabrication Facility, Cornell University, Ithaca, NY.

Electron beam lithography (EBL) is the most widely used process for the fabrication of nanoscale features. The flexibility of the technique is unsurpassed. In academic research, EBL allows scientists to write patterns for the study of quantum physics, nanomechanics, biophysics, and optics. In industry, high resolution electron beam systems are used for low cost prototyping, and for the fabrication of reticles. Over the past 30 years, many technological advances have made nanometer scale EBL more accessible. These advances include enhanced resist processing, better electron sources, and highly accurate stages. Resists and processes are well refined now. It is possible to use chemically amplified resists which have a high resolution (< 30 nm features) and can expose much faster than conventional resists. Thermal field emission electron sources provide high brightness as well as long term stability. High energy electron beams (100 kV) allow for a wider process latitude in the fabrication of sub 20 nm structures. Systems with highly accurate laser interferometer stages can place features with overlay errors of less than 5 nm. These and other interesting results from modern electron beam systems will be discussed, as well as some brief history of the technology.

9:30 AM J3.3
SUB-10 NANOMETER LITHOGRAPHY VIA ELECTRON-BEAM LITHOGRAPHY AND ELECTRODEPOSITION. Mingshaw W. Wu, Lydia L. Sohn, Princeton University, Dept. of Physics, Princeton, NJ.

The ability to fabricate structures on the sub-10 nm length scale is a long sought-after goal. While a great deal of emphasis has been placed on such fabrication techniques as scanning probe microscopy and self-assembly, to date, there is no accepted universal strategy which enables investigators to access the sub-10 nm length scale on an arbitrary substrate with a variety of materials. We have developed a combination of technqiues which allows us to do just this: to access the sub-10 nm length scale reliably and reproducibly in a number of different materials on any given substrate. First, we have developed a resist-treatment method which enables us to use electron-beam lithography to fabricate structures on the 10 nm length scale. Second, we have developed an electroplating technique to reduce this length scale to 1 nm. A particular advantage to our combination lithography is that we can fabricate structures of increasing complexity. In this talk, we will discuss our fabrication strategy and demonstrate our success in using this strategy for sub-10 nm lithography.

10:15 AM *J3.4
NANOFABRICATION WITH IONS. John Melngailis, University of Maryland, Department of Electrical and Computer Engineering, College Park, MD.

To pattern a surface with ions part of the surface has to be irradiated and part has to be unirradiated. There are three ways of producing a patterned dose of ions on a surface: scanned focused (point) ion beams, proximity stencil masks irradiated with a collimated ion beam, and projection of the stencil mask pattern through ion optics. There are a number of ways of using the patterned irradiation by ions to alter the surface, including: exposure of resist (ion lithography), direct milling of the surface, induced chemical reaction on the surface for both material addition and removal, and implantation of the surface layer. While the finest ion pattern that can be produced by any of the irradiation techniques is well into the nanometer regime, the dimensions of the pattern actually formed in the surface are influenced also by effects such as ion straggle, scattered atom straggle, scattered electron range, material swelling due to amorphization, and redeposition effects. In resist exposure, light ions, e.g. protons, have the advantages of very minimal straggle, and an ion range comparable to the desired resist thickness. This is one of the key considerations that is motivating the European project to develop ion projection lithography. In focused ion beam milling, the achievable aspect ratio of trenches is limited by redeposition. However, in diamond 20: 1 aspect ratio deep trenches have been fabricated as well as linewidths down to 28nm. In ion induced deposition the lines deposited are often wider than the minimum beam diameter, but features down to 100 nm width can be achieved. Particularly for focused ion beam fabrication of nanostructures the advantage is that resistless material removal and addition is available and that it is not limited to planar surfaces.

10:45 AM *J3.5
ION PROJECTION LITHOGRAPHY FOR NANOPATTERNING. Wilhelm Brünger and Anton Heuberger, Fraunhofer Institut Siliziumtechnologie, Munchen, GERMANY.

Ion Projection Lithography (IPL) combines the capabilities of high resolution (< 50 nm) and high throughput because of the parallel printing process using a mask. In addition IPL has the unique possibility of resistless surface modification avoiding additional process steps for extremely defect sensitive applications. The fabrication process of the open stencil masks has been facilitated by applying mainly standard wafer processes. E-beam written structures are transferred by deep trench etching into an SOI-wafer with final thinning of the membrane area using the oxide layer as etch stop. Standard DUV chemically amplified resists have shown high sensitivity of 10^{12} He^+ ions/cm^2 at 75 keV ion energy, allowing for exposure times of below 1 sec in the IPL-system in Berlin. Resist parameters are now optimized to reach a resolution below 50 nm for ion exposure.
Recently IPL has been applied for the patterning of thin magnetic film. Intermixing of sandwich layers is created by direct ion impact without using a resist mask on the sample. This IPL process has the advantage of low defect density and small surface topography change which is important for the production of prepatterned single domain magnetic nano islands for data storage.

11:15 AM J3.6
FABRICATION OF SUB 0.1 MICRON STRUCTURES USING INERT AND REACTIVE ION BEAM ETCH TECHNIQUES. Jhon F. Londono, Kurt E. Williams, Veeco Instruments, Inc., Plainview, NY.

Use of a Radio Frequency Inductively Coupled (RF-ICP) Ion Source to Etch Sub 0.1 Micron Structures is Demonstrated. 350 mm Diameter Broad Ion Beams, Using a Combination of Inert Argon and Reactive Oxygen Plasmas, Were Used to Produce Structures With Features Below 100 Nanometers On Aluminum Films. Structures With Nearly Vertical Sidewalls and Free of Trenching and Redeposition Effects Were Successfully Fabricated.

11:30 AM *J3.7
FABRICATION OF NANOSTRUCTURES USING SOFT LITHOGRAPHY. George M. Whitesides, Harvard University, Dept. of Chemistry and Chemical Biology, Cambridge, MA.

This talk will discuss recent work in soft lithography and related techniques. Topics of particular current interest include techniques that generate sub-100 nm features using controlled generation of defects or near-field optical methods, and techniques that are based on microelectrochemistry.

SESSION J4: NEW CONCEPTS FOR MATERIALS DESIGN
Chairs: Kenneth E. Gonsalves and William Hinsberg
Tuesday Afternoon, November 30, 1999
Boston College (M)

1:30 PM *J4.1
SELF-ASSEMBLED MONOLAYER ELECTRON BEAM RESISTS.

D.L. Allara, C.A. Mars, K. Sesdhadri, R.J. Davis, M. Garrett, Materials Research Institute, Pennsylvania State University, University Park, PA.

The ability to pack molecules via self-assembly methods into dense, nm-thickness films on semiconductor surfaces offers opportunities to use these films for ultrahigh resolution lithographic patterning. Previous work has shown that self-assembled monolayers can act as both positive and negative contrast electron beam resists. This talk will cover current work on various aspects including methods for improving the packing density of the films on a variety of substrates, e.g., Si, GaAs and InP, and on understanding the mechanisms of defect formation during the etching process.

2:00 PM J4.2
ANISOTROPIC ORGANIC/INORGANIC RESISTS: A NOVEL CONCEPT FOR ELECTRON PROXIMITY EFFECT REDUCTION. Lhadi Merhari, CERAMEC R&D, Limoges, FRANCE; Kenneth E. Gonsalves, Institute of Materials Science and Dept of Chemistry, University of Connecticut, Storrs, CT.

Electron projection lithography is considered to be one of the best candidates for 100 nm production circuits. One of the major problems that hinders its development is not related to machine fabrication issues but to electron proximity effects, which stem from fundamental electron-polymer interactions. During the last two decades, efforts to reduce the electron proximity effects have essentially focused on the optimization of the resist exposure by means of dose modulation correction programs. We propose a novel approach where the structure of the resist can be tailored so that controlled anisotropy is introduced to laterally constrain the electron scattering. This novel approach does not require the use of high-voltage electron beams nor the processing of large amount of data, which is a significant economic advantage. Some concepts for the synthesis of these anisotropic resists will be discussed.

2:15 PM J4.3
NEW HIGH RESOLUTION LIQUID CRYSTAL ELECTRON BEAM RESISTS. A.P.G. Robinson, R.E. Palmer, Nanoscale Physics Research Laboratory, School of Physics and Astronomy, The University of Birmingham, Birmingham, UNITED KINGDOM; T. Tada, T. Kanayama, Joint Research Center for Atom Technology, National Institute for Advanced Interdisciplinary Research, Tsukuba, JAPAN; M.T. Allen, J.A. Preece and K.D.M. Harris, School of Chemistry, The University of Birmingham, Birmingham, UNITED KINGDOM.

We report the development of a new family of electron beam resists based on liquid crystalline polysubstituted derivatives of triphenylene. These new resists show excellent performance in terms of both high resolution and high durability to plasma etching. Films of the derivatives have been produced in a controlled manner via room temperature spin coating on hydrogen terminated silicon substrates. The dissolution behaviour of the derivatives in various organic solvents was altered by exposure to a 20 keV electron beam. For instance the solubility of the derivative hexapentyloxytriphenylene, in polar solvents, was substantially increased by electron doses greater than ~ 3 (10^{-4} C/cm^2 (positive tone behaviour). Doses greater than ~ 2.5 (10^{-3} C/cm^2 led to negative tone behaviour in both polar and non-polar solvents. Other derivatives also demonstrated a reduction in their dissolution rate for doses between ~ 1 (10^{-3} and ~ 7 (10^{-3} C/cm^2. The derivative sensitivity was found to be roughly proportional to the molecular mass. Negative tone patterns were found to have an etch durability ~ 70 % greater than that of a conventional novolac based negative tone resist (SAL601). The performance of these new resists has been demonstrated by the definition of line and space patterns with a resolution of ~ 14 nm, whilst structures with an aspect ratio of ~ 50 to 1 were etched into the silicon substrate.

2:30 PM J4.4
POLYMER-INORGANIC NANOCOMPOSITES: HIGH CONTRAST AND HIGH SENSITIVITY RESISTS FOR NANOLITHOGRAPHY. Kenneth Gonsalves, Henry Li, Hengpeng Wu, Institute of Materials Science and Dept of Chemistry, University of Connecticut, Storrs, CT; Lhadi Merhari, CERAMEC R&D, Limoges, FRANCE.

Novel resist systems for X-ray lithography (XRL) specifically optimized in terms of contrast enhancement are described. Based on terpolymers of methyl methacrylate (MMA)-tertiary butylacrylate (TBA)-polyhedral oligosilsesquioxanes (POSS) synthesized by solution polymerization, these systems were optimized by a combinatorial approach. It is shown that the molar ratio of MMA/POSS=85.7/14.3 leads to maximum contrast (23.5) without sacrificing the sensitivity (1350 mJ/cm^2) which remains comparable to that of standard PMMA. Such major contrast enhancement shows that the above organic/inorganic nanocomposites are promising candidates for sub-100 nm lithography.

2:45 PM J4.5
CARBON DIOXIDE - DILATED BLOCK COPOLYMER TEMPLATES FOR NANOSTRUCTURED MATERIALS. Garth D. Brown, James J. Watkins, Univ. of Massachusetts, Dept. of Chemical Engineering, Amherst, MA.

The fabrication of nanostructured devices will require the assembly of metal or semiconductor domains of precise size, shape and connectivity into periodic arrays with long-range order. One route to providing such morphological control is the use of nanostructured templates that are ideally robust, net shape and amenable to precise alignment over macroscopic length scales. Block copolymer melts meet these criteria, but to date their use as practical 3-D templates has been impeded by mass-transfer resistance to reagent transport over bulk-scale dimensions. In this paper, we demonstrate that CO_2 -dilated copolymers are viable reaction media and thus versatile templates for the preparation of periodic nanocomposites. Specifically organometallic compounds (metal precursors) are dissolved into compressed carbon dioxide and infused into polystyrene-block-poly (acrylic acid) or polystyrene-block-poly(vinylpyridine) copolymers. Upon infusion, the acid (or pyridine) block selectively binds the metal precursor and the excess is removed from the polystyrene phase by subsequent CO_2 extraction. Reduction of the bound organometallic with hydrogen or hydrogen sulfide within spherical domains of an asymmetric copolymer, for example, yields the desired metal or semiconductor clusters (10 nm), which remain positioned on the copolymer lattice. The key to the process is sorption of low weight fractions of carbon dioxide, which significantly enhances reagent diffusivity without destroying the copolymer morphology. The composites are characterized by transmission electron microscopy, x-ray scattering and electron diffraction.

3:30 PM *J4.6
FULLERENE-INCORPORATED NANOCOMPOSITE RESIST SYSTEM FOR NANOLITHOGRAPHY. Tetsuyoshi Ishii, Toshiaki Tamamura, NTT, Basic Research Labs, Atsugi, JAPAN; Hiroshi Nozawa, NTT, Photonics Labs, Atsugi, JAPAN.

A nanocomposite resist system that incorporates sub-nm fullerene molecules (C_{60} and/or C_{70}) into a conventional resist material as a nanometer range resist is proposed. Fullerene has chemical and physical resistant characteristics, and its incorporation reinforces the original resist film, leading to substantial improvements in resist performance: etching resistance, pattern contrast, mechanical strength, and thermal resistance. We have confirmed improved resist performance in a system composed of a positive-type electron beam resist, ZEP520, and C_{60}, or a C_{60}/C_{70} mixture. Film thinning by enhanced etching resistance is particularly advantageous for nanometer pattern fabrication because a thinner film generally improves resolution. This has been demonstrated through the fabrication of a 30-nm gate HEMT, in which the dimension is clearly delineated in a 200 nm film, but not in a 250 film. The sensitivity of nanocomposite resist readily changes with the fullerene content due to the dissolution inhibiting effect of fullerene, and this characteristic can be applied to construct a fullerene-incorporated bilayer resist system for the lift-off process. A bilayer comprising a fullerene-incorporated ZEP top layer and a pure ZEP bottom layer provides an ideal overhang pattern and facilitates metal lift-off. Using such a bilayer, we have successfully fabricated an array of dot patterns with nanometer dimensions for a quantum box structure and a nanoprinting mold. Presently, applications of ZEP nanocomposites and composites made of systems other than ZEP as well are limited by the poor solubility of fullerene. However, the solubilitiy of fullerene can be greatly enhanced by introducing some solubility-promoting functional group to a fullerene molecule. Solubility enhancement by fullerene derivatives is examined for a higher degree of fullerene incorporation and better sensitivity characteristics in future nanocomposite resist systems.

4:00 PM *J4.7
LINKING OF ATOMIC AND CONTINUUM SIMULATIONS FOR NANOFABRICATION. Klavs Jensen, Seth Rodgers, Raj Venkataramani, Massachusetts Institute of Technology, Department of Chemical Engineering, Cambridge, MA.

The coupling of molecular level simulations with traditional continuum phenomena descriptions is increasingly important in predicting vapor phase growth of structures because of the need to understand the relationship between processing and device performance. This development is further driven by the continual reduction in device dimensions into the nanometer regime, the rapid development pace, and the introduction of new materials into electronic device fabrication. The development of predictive, efficient models that bridge across multiple length and time scales raises new challenges in terms of simulation strategies, numerical algorithms, and experimental validation. These are exemplified through studies linking quantum chemistry, molecular dynamics (MD), kinetic Monte Carlo (MC), and macroscopic finite element simulations. Process examples

are drawn from chemical and physical vapor deposition of metals and semiconductors. Specifically, experimental observations and quantum chemistry predictions of elementary surface reactions are incorporated into MD and MC simulations to provide new understanding of microstructure evolution. By flux balances and level set methods, the results of these computations are subsequently incorporated into self-consistent feature and reactor scale models. Comparisons with experimental data are given at each length scale along with a discussion of the type of data needed to validate multiscale models.

4:30 PM J4.8
A NEW HIGH PERFORMANCE CA RESIST FOR E-BEAM LITHOGRAPHY. Ranee Kwong, Wu-Song Huang,Wayne Moreau, Robert Lang, Chris Robinson, IBM Microelectronics, Hopewell Junction, NY; David Medeiros, Ari Aviram, Richard C. Guarnieri, Marie Angelopoulos, NY.

There are three major applications of electron beam (e-beam) technology: (1). optical mask fabrication (2). direct write for device fabrication and (3). more recently projection e-beam printing. For these technologies, advanced resists are needed which couple high resolution, high contrast, high sensitivity, and high dry etch resistance. Resist sensitivity is an important factor in the throughput of these technologies. It is currently projected that a sensitivity of at least 5uC/cm2 will be needed on a high KeV e-beam tool to provide sufficient throughput. In this presentation we will discuss a new ketal based chemically amplified resist which exhibits excellent lithography (resolution of 75nm lines/space has been demonstrated), is robust toward airborne base, compatible to 0.263N TMAH aqueous developer and insensitive to baking temperatures. We will discuss the resist chemistry, its lithographic performance including various methods of enhancing the sensitivity. It will be shown that 5uC/cm2 can be attained on a 75KeV tool by modification of resist formulation. In addition, we will discuss factors controlling image integrity at sub100nm resolution features. Keywords: photoresists, E-beam, chemical amplification, ketals

4:45 PM J4.9
LOCAL ETCHING OF a-C:H FILMS BY NANOPROBE. Arcadii Redkin, Alexandre Fioshko, Gennady Mikhailov, Dept. of Nanoelectronics, Institute of Microelectronics Technology, Chernogolovka, RUSSIA.

The prospective material for nanomask fabrication is amorphous hydrogenated carbon (a-C:H), possessed many attractive properties for potential application as a resist. We developed a nanomask fabrication using direct local etching of the amorphous hydrogenated carbon (a-C:H) films. The films of 10-100 nm thick were grown by plasma assisted deposition. The film surface was characterized by atomic force microscope (AFM), low surface roughness at a level of 1 nm was found. We used conducting (p-Si) cantilever of AFM to stimulate local chemical reactions on the film surface. It was found for the first time that a conducting cantilever under applied pulse potential in 3-4 V stimulates the local etching of a-C:H films. The etching process reproducibly continued under control ambient medium and the etching rate was directly proportional to the number of cantilever scans. It was also in dependence on the amplitude of potential, ambient humidity, and the pressing force applied to the cantilever. The range of etching depths was 1-100 nm. Found lateral resolutions of the local etching depend on the depth etching. It was larger than 15 nm and limited by a curvature radius of the cantilever tip. The etching process is due to the chemical reaction between a-C:H films and oxygen containing compounds absorbed on the film surface. Local electrical field gained by the cantilever tip in the vicinity of the film surface stimulates chemical reactions initiated at some threshold value of applied electrical potential.

SESSION J5: NONCONVENTIONAL LITHOGRAPHIC TECHNIQUES AND ADVANCES IN DEVICE NANOFABRICATION

Chairs: Hersong Chen and John Melngailis
Wednesday Morning, December 1, 1999
Boston College (M)

8:30 AM *J5.1
NANOSTRUCTURE FABRICATION USING ELECTRON BEAM. Shinji Matsui, Himeji Institute of Technology, Hyogo, JAPAN.

Nanofabrication developed by using electron beam (EB) are described. Ten-nm structures of organic positive and negative resist patterns have been achieved by using a commercially available EB lithography system with energy of 30-50 keV. The self-developing properties of an AlF3-doped LiF inorganic resist have been studied for sub-10-nm lithography. By optimizing the inorganic resist film quality, 5-nm linewidth patterns with 60-nm periodicity were directly delineated under a 30-keV EB. Moreover, EB-induced deposition is described as an interesting method for nanofabrication. An novel approach for nanolithography using de Broglie wave has been developed. Line and dot patterns with 100-nm periodicity were exposed on a PMMA resist by EB holography with a thermal field-emitter gun and an electron biprism. This technique allows us to produce nanoscale periodic patterns simultaneously. Furthermore, the possibility of nanostructure fabrication by atomic-beam holography has been demonstrated by using a laser-trap technique and a computer-generated hologram made by EB lithography.

9:00 AM *J5.2
ADVANCES IN NANOIMPRINT LITHOGRAPHY. S.Y. Chou, W. Zhang, J. Wang, M.T. Li, L. Zhuang, H. Tan, and S. Schablitsky, Nanostructure Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ.

Previously, nanoimprint lithography (NIL) demonstrated sub-10nm feature size, but has a small imprint area, relatively high process temperature and pressure and bubbles existing in features of feature size larger than 50 mm. [1] Here, we present significant advances in developing NIL in three areas. First, new generation of NIL machine has been built and could process 4 inch wafer and make uniform result over entire wafer. Not only nanometer features but also large features (such as Lines of linewidth from 3 to 50 microns and line length of 2 cm) can be imporinted with good uniform and high fidelity. Second, we have developed the second-generation roller nanoimprint lithography system that has the advantage of a good uniformity over 4 inch wafer, a high pattern aspect ratio, fast processing speed, and automatic control of operation. They includes (1) sub-50 nm features and an aspect ratio better than 4, and (2) ring patterns with 60 nm linewidth and 70 nm spacing. Third and finally, we have developed step-and-repeat NIL systems that has patterned 100 nm linewidth gratings with 200 nm period in a step-and-repeat fashion. [1] S.Y. Chou, P.R. Krauss, and P.J. Renstrom, Science, 272, 85 (1996); and S.Y. Chou, P.R. Krauss, W. Zhang, L. Guo and L. Zhuang, J. Vac. Sci. Technol. B 15(6), 2897 (1997).

9:30 AM J5.3
CHANNEL STAMPING: PATTERNING ORGANIC AND INORGANIC MATERIALS. Fred F. Lange and Geoff Fair, Materials Department, College of Engineering, University of California, Santa Barbara, Santa Barbara, CA.

An elastomeric stamp, developed by Whitesides and colleagues, is used by filling the channels, via spin coating, with a solvent containing either polymer molecules to produce a polymer pattern for masking vapor phase device fabrication or precursor molecules to produce a inorganic pattern during a subsequent heat treatment. During solvent evaporation, the polymer or precursor molecules are left behind and can transferred to a substrate providing certain capillary conditions are present in the liquid state, and certain fracture mechanics criteria are satisfied during drying and stamping. These conditions/criteria are discussed with examples.

9:45 AM J5.4
PHOTO AND SCANNING PROBE LITHOGRAPHY USING ALKYLSILANE SELF-ASSEMBLED MONOLAYERS. Hiroyuki Sugimura, Takayuki Hanji and Osamu Takai, Department of Materials Processing Engineering, Graduate School of Engineering, Nagoya University, Chikusa Nagoya, JAPAN.

We report here organic resist films of a few nm in thickness applicable to photolithography and scanning probe lithography. These resist films were prepared on oxide-covered Si substrates through chemisorption of organosilane molecules and their spontaneous organization. The films belong to a class of materials referred to as self-assembled monolayer (SAM), and have excellent uniformity in molecular scale. First, an alkylsilane SAM prepared through chemical vapor deposition was photopatterned as follows. A SAM covered Si substrate was irradiated under vacuum (10 Pa) with vacuum ultraviolet (VUV) light through a photomask contacting the substrate surface. An Xe excimer lamp of 172 nm in wavelength was used as the light source. VUV light dissociatively excites C-C and C-H bonds resulting in the decomposition of organic molecules. Consequently, the SAM was decomposed in the photoirradiated region and a photomask image was transferred to the SAM. Next, using an atomic force microscope (AFM) with an electrically conductive probe, another SAM-Si substrate was patterned by flowing current through the AFM-probe/sample junction. The SAM was electrochemically degraded in the region where the AFM probe had been scanned. The probe-scanning pattern was thus printed on the SAM. The both photo-printed and AFM-genereated patterns were successfully transferred into the Si substrates through chemical etching. At present, the minimum resolutions of these photo and AFM-based lithographies were 200 and 20 nm, respectively. In addition, we have succeeded in combining these two types of lithography based on the

SAM resist which was first exposed with VUV light and, then, nanopatterned by AFM. The total throughput of the scanning probe lithography can be improved by combining photoprinting and AFM-drawing. [1] H. Sugimura and N. Nakagiri, Appl. Phys. A. 66 S427 (1998).

10:30 AM *J5.5
GATE TECHNOLOGY ISSUES FOR SILICON MOS NANOTRANSISTORS. D.M Tennant, Bell Laboratories, Lucent Technologies, Holmdel, NJ; G.L. Timp, L.E. Ocola, M. Green, T. Sorsch, A. Kornblit, F. Klemens, R. Kleiman, D.A. Muller, Y. Kim, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; and W. Timp, University of Illinois, Champaign-Urbana, IL.

We report on progress and gate technology issues in scaling both NMOS and PMOS conventional planar transistors to a physical gate length of 30nm and an expected effective channel length of 10 nm. For this work, device fabrication employs direct write e-beam lithography to form a single lithography level ring structure capable of exploring the practical limits of gate processing. Other processing features include ultrathin gate dielectric formation ($\sim$ 0.6nm); highly selective transformer coupled plasma (TCP) etching; and low energy ion implantation. We demonstrate lithographically defined resist features as narrow as 28 nm that were obtained with NEB 31, a negative tone chemically amplified resist. Electron energy loss spectroscopy is used to analyze the interface of the gate dielectric region to understand the limits of scaling of silicon dioxide. Scanning capacitance microscopy is shown to be useful in determining the effective channel lengths and source drain junction depths on cross-sectioned devices to calibrate process simulation programs and thereby optimize the transistor design. We present DC electrical results obtained for high performance NMOS and PMOS nanotransistors made using this process. Based on measured performance, simulations are presented which predict sub threshold current for the NMOS transistors with gate lengths down to 26nm. These calculations can be used to both infer limits on large scale integration and also to estimate process latitude for CD control and edge roughness in the gate formation sequence of CMOS technology beyond 40 nm.

11:00 AM J5.6
FABRICATION OF ISOLATED NANOPARTICLE CIRCUITRY VIA LENSLESS OPTICAL TWEEZING. G.C. Spalding, M.T. Dearing, Illinois Wesleyan Univ, Dept of Physics, Bloomington, IL.

We propose a novel method for trapping a nanometer-scale particle into a stable structure useful for a variety of interesting electrical measurements. The particle can be dielectric or metallic, magnetic or non-magnetic. Our methodology was developed, in part, to ensure the absence of extraneous nanoparticles in the region of the device under test; it also has the further benefit of providing a feedback mechanism which indicates when a nanoparticle has been successfully trapped. In particular, we propose irradiating a substrate containing a tiny etch-pit hole. On the transmission side of the substrate, the diffracted or evanescent optical fields should contain large enough gradients to localize a nanoparticle to the region of the hole.

11:15 AM J5.7
THE NOVEL TECHNIQUE OF NANOMETER-SIZE FABRICATION BY USING CONVENTIONAL PHOTOLITHOGRAPHY. Shingi Hashioka and Hideki Matsumura JAIST, Ishikawa, JAPAN.

The development of novel technique is required for realizing nano-scale devices. Fabrication of nanometer patterns using tips of scanning tunnel microscopy has been reported. However, it cannot be an industrially acceptable technique. Thus, if the conventional lithographic techniques such as photolithography can be applied to fabricate such nanometer-size structures with a few tens nm, it would be useful. In this research a novel nano-technology is proposed. A contact pattern-mask with nanometer-size slits is fabricated by the combination of conventional photo-lithography with anodic oxidation method. The proposed fabrication processes are as follows. 1) The CeO_2 is deposited on the Si(111) substrate and Ti is deposited on the CeO_2 layer. CeO_2 is used as an interlayer to protect the substrate. 2) The photoresist is coated on it and a half part of it is exposed by light and patterned. After patterning, a half part of photoresist is removed and another half part of Ti appeared is etched by reactive ion etching. 3) The edge of the Ti layer under the resist is anodized laterally to convert into TiO_x. The thickness of TiO_x obtained by anodic oxidation can be controlled in the ranges of several-tens of nanometer by changing the anodic voltage. 4) The Ti layer is again deposited over the whole surface, and the Ti over the resist is removed by a lift-off technology. 5) The TiO_x is etched, and thus metal nanometer slit pattern-mask on the CeO_2 layer is obtained. 6) The CeO_2 layer is etched, and thus nanometer slit pattern-mask is obtained. The minimum width is about 10nm. As an application of nanometer slit mask, trenches with nm size can be fabricated on the Si substrate by etching Si through the slit. This result indicates that the nanometer slit mask can be useful for the fabrication of the nano-scale device such as a single electron transistor and metal/insulator tunnel transistor.

11:30 AM J5.8
LOCALIZED CHARGE STORAGE IN CeO_2/Si(111) BY ELECTROSTATIC FORCE MICROSCOPY. J.T. Jones, P.M. Bridger, O.J. Marsh, T.C. McGill, California Institute of Technology, Pasadena, CA.

In this report, the local patterning of charge into CeO_2/Si structures by scanning probe microscopy is examined. An electrostatic force microscope (EFM) has been used to write and image localized dots of charge on to double barrier CeO_2/Si/CeO_2/Si(111) structures. By applying a large tip bias V_{TIP} = 6-10 V and reducing the tip to sample separation to 3-5 nm, arrays of charge dots 60-200 nm FWHM of both positive and negative charge have been written. The total stored charge is found to be Q = $\pm$(20-200) e per charge dot. These dots of charge are shown to be stable over periods of time greater than 24 hrs, with an initial charge decay time constant of $\tau \sim 9.5$ hrs followed by a period of much slower decay with $\tau > 24$ hrs. Charge decay time constants are found to be dependent on the thickness of the lower CeO_2 tunneling barrier. The dependence of dot size and total stored charge on various writing parameters such as tip writing bias, tip to sample separation, and write time is examined.

11:45 AM J5.9
SPM BASED LITHOGRAPHY FOR NANOMETER SCALE ELECTRODES FABRICATION. Andrea Notargiacomo, Polo Nazionale Bioelettronica, Marciana (Li), ITALY; Ennio Giovine, Unità INFM, Dip. di Fisica "E. Amaldi", Università di Roma TRE, Roma, ITALY; Elena Cianci, Osservatorio Astronomico di Roma, Monteporzio Catone, ITALY; Vittorio Foglietti, Istituto di Elettronica dello Stato Solido (IESS), CNR, Roma, ITALY; Florestano Evangelisti, Istituto di Elettronica dello Stato Solido (IESS), CNR, and Unità INFM, Dip. di Fisica "E. Amaldi", Università di Roma TRE, Roma, ITALY.

SPM assisted nanolithography is a very attractive technique in terms of low-cost, patterning resolution and positioning accuracy. Our approach makes use of a commercial AFM and silicon probes to build directly simple nanostructures, such as metal electrode pairs, for application in novel quantum devices. As a first attempt we performed a direct material removal from metal stripes thus producing gaps in the nanometer range. This technique is strongly limited by the short life-time of the probes, whose wearing determines also a widening of the fabricated gaps. To overcome these limits, which mainly stem from the hard interaction between the probe and the sample, an alternative technique was considered. A multilayer sample preparation, already proposed to pattern a flat silicon surface (1), was suitably adapted to induce nanometer size modifications on pre-existing metal structures. The first step involved metal stripes and sacrificial layer preparation, including a soft polymer film deposition that was optimized to achieve conformal growth and smooth surface. These features are necessary to prevent the probe wearing and to locate exactly the region of the sample where the modifications are desired. Then the AFM probe was used to obtain a pattern by selectively removing a very thin metal layer deposited on top of the polymer. As the final step, by means of dry and wet etching processes, a pattern transfer was performed onto the underlying metal structures, obtaining nanometer size gaps. In conclusion we have optimized a reliable patterning technique showing high probe life-time and optimal positioning accuracy, both ensured by a suitable choice of the nature and thickness of the sacrificial layers used. Sub-100 nm patterning was successfully performed with high reproducibility leading to metal nanoelectrode pairs.
(1) Hu S. et al., J. Vac. Sci. Technol. B 16 (5), Sep/Oct 1998, p. 2822-2824.