Nanometer-scale Science and Technology
Room 101D - Session NS-MoM

Nanopatterning and Nanofabrication + 3D

Moderators: Keith Brown, Boston University, Indira Seshadri, IBM Research Division, Albany, NY

8:20am **NS-MoM1 Fabrication and Characterization of Carbon Nanotube-Based Electronic Devices***, **Zhigang Xiao**, S. Budak, A. Kassu, X. Crutcher, T. Strong, J. Johnson, R. Hammond, J. Gray, A. Reynolds, R. Moten,* Alabama A&M University

Single-walled carbon nanotubes (SWCNTs) are used widely in fabricating nanoelectronic devices because of their unique electrical properties. We report the fabrication of carbon nanotube field-effect transistors (CNTFETs)-based inverter and ring oscillator electronic circuits using the dielectrophoresis (DEP)-aligned single-walled carbon nanotube mesh networks. The electrical property of the fabricated CNTFET-based devices was measured. The CNTFET-based inverter shown excellent electrical transfer characteristics, while the CNTFET-based ring oscillator demonstrated oscillation characteristics, denoting that the CNTFET-based circuits can function well for the application of electronic circuits. The DEP-based fabrication of carbon nanotube electronic circuits is wafer-scale, and compatible with the integrated circuit (IC) fabrication.

8:40am **NS-MoM2 Multi-Material Two Photon and Direct Write Lithography for Photonics, Phononics and Mechanics***, **Steven Kooi**,* Massachusetts Institute of Technology

A combination of two-photon (2PL), holographic and direct write lithography, in positive and negative tone photoresists as well as photopatternable hydrogel materials, is used to produce nano and microscale structures for photonic, phononic and mechanical applications. The lithographic processes are described as well as the conversion of the 3D structures into higher index of refraction materials (Si, Ge and metals) for photonic applications and engineered modulus materials for phononic and mechanical applications by atomic layer deposition, chemical vapor deposition, chemical etching and ion etching techniques. Standard piezo stage scanning two-photon lithography is used to produce 3D structures as well as an upgraded design that incorporates galvo-scanning mirrors that greatly increase the writing speed and area.

The conversion of polymeric structures to higher index materials allows us to access more interesting and measurable optical properties in the visible wavelength range. Optical measurements include reflectivity to characterize optical bandgaps and to evaluate structural uniformity and quality. In addition, near field scanning optical microscopy (NSOM) techniques are used to follow light propagation through engineered photonic structures. These results are compared to theoretical predictions of optical properties and are used to evaluate not only the defect density in the printed structures, but also the quality of the multi-step conversion process. The 3D structures are also characterized by serial focused ion beam (FIB) milling and imaging.

Phononic and mechanical 3D structures are also produced by the same lithographic techniques. These materials are tested by light scattering techniques to evaluate phononic properties as well as static and dynamic mechanical measurements to investigate size and structure dependent mechanical properties. 2PL is also used to produce periodic structures that are used in laser-induced shock wave imaging experiments. These experiments are designed to study the influence of the periodic structures on the propagation and/or mitigation of shock waves.

9:00am **NS-MoM3 Applications of 2-photo 3D Stereolithography to Aerial Microrobots and Air-Microfluidics***, **Igor Paprotny**,* University of Illinois at Chicago **INVITED**

Additive manufacturing, commonly called 3D printing, is currently revolutionizing manufacturing worldwide. Two-photon polymerization has in the last decade been used as an novel 3D stereolithography method that enables the fabrication of microscale structures with a resolution on the order of 100s nanometers. The ability to 3D print microscale structures enables development of novel microelectromechanical systems (MEMS) that transcend traditional top-down micromachining processes. This talk will review the theory of 2-photon polymerization and the applications of this method to microstereolithography. I will also review two novel applications of this technique to MEMS devices fabricated in the Micromechatronic Systems Laboratory at the University of Illinois at Chicago. One application is the investigation of microscale flight, where two-photon stereolithography is used to develop test structures and devices that hover upon application of a localized thermal gradient. New results, enabled by our ability to 3D print 'microflier' designs with varying geometry, show similarity to flight performance observed in microscale flying insects. This talk will also describe the application of two-photon microstereolithography to air-microfluidics, where the creation of microfluidic channels with complex geometries have tremendous applications to the development of lab-on-a-chip sensors for air quality and gas measurements. Several examples of such air-microfluidics circuits are presented and discussed.

9:40am **NS-MoM5 Elucidating Proximity Effects during Direct-Write Synthesis of Complex 3D Nanostructures***, **Brett Lewis**,* University of Tennessee*; J.D. Fowlkes,* Oak Ridge National Lab*; R. Winkler,* Graz Centre for Electron Microscopy, Austria*; H. Plank,* Graz University of Technology, Austria*; P.D. Rack,* University of Tennessee

Cutting edge 3-dimensional nanofabrication techniques are essential for the future technological advancement in many fields and applications ranging from metamaterials to memory devices. One technique to realize truly flexible 3D nanoprinting is focused electron beam induced deposition (EBID), which uses a focused scanning electron beam to decompose precursor molecules adsorbed onto a substrate surface. The electron/precursor/solid intersection generates a deposit composed of the desired material and shape dictated by the prescribed scanning parameters. EBID has the advantage of being compatible with a wide range of materials, substrates and complex geometries at the nanoscale.

In this work, we will overview the relevant electron/precursor/solid interactions and present a systematic study of the geometric dependence of unwanted proximity effects that occur during the deposition process. Notably, we present a solution designed to minimize proximal deposition by appropriately adjusting the scanning parameters and beam conditions dependent on the desired final geometry. Specifically, we have developed a computer aided design (CAD) program that automatically calibrates the scanning pattern by calculating the predicted contribution from nearest neighbor elements. Our program has been demonstrated for use with platinum and gold structures grown from the organometallic precursors *MeCpPt(IV)*Me_3 *and Me2Au(acac)* and *the principles can easily be adapted to other material systems. Furthermore, we will demonstrate a laser-assisted process which significantly reduces contamination in the nanoscale deposits.*

10:00am **NS-MoM6 Surface Textures with Asymmetric Wetting and Optical Properties Enabled by Two-Photon Direct Laser Writing***, **Nick Lavrik**,* Oak Ridge National Laboratory*; C. McKown,* UT/ORNL Bredesen Center

Over the last decade, advances in direct laser writing (DLW) using two-photon polymerization have led to development and proliferation of user friendly commercially available tools that extend the concept of additive manufacturing into the nanoscale and enable a researcher with facile and flexible means of fabricating arbitrary complex 3D elements with submicron fidelity. Using one of such recently emerged tools, namely a Photonic Professional GT system (Nanoscribe GmbH), we have explored various asymmetric motifs with the purpose of creating surface textures with unique wetting and optical properties. Starting with simple bio-inspired elements, such as arrays of deformed pillars and fish scale elements, we design and create surface textures that exhibit asymmetric contact angle hysteresis as well as strongly anisotropic reflectivity.

The unique flexibility in creating intricate 3D elements offered by two-photon DLW allows us to elucidate relationships between the subtle variations in the surface topology and changes in the targeted functionalities. Examples of model systems based on asymmetric textures with characteristics promising for a number of applications will be discussed. This talk will also discuss how two-photon DLW can be integrated with and augmented by more conventional wafer scale processing and thin film technologies. Of our particular attention are fabrication sequences that combine two-photon DLW with ALD and thermal post-processing with the goal of creating asymmetric textures represented by more diverse classes of materials beyond crosslinked photopolymers.

10:40am **NS-MoM8 New 3D Structuring Process, by Ion Implantation and Selective Wet Etching**, ***Lamia Nouri****, N.P. Posseme, S.L. LANDIS, F.G. GAILLARD, F.M. MILESI,* CEA, LETI, MINATEC Campus, France

Silicon patterning is a one of the most important steps in nano/micro fabrication, especially for mico/nano electro-mechanical systems (MEMS/NEMS), optoelectronic devices etc ... The fabrication schemes that microelectronics had boosted for decades for the production of integrated circuits, (based essentially on layering and planar patterning stacks of semiconductors, metals, and dielectrics) do not meet the new structuration's requirements. Indeed, for the new emerging fields which may involve complex 3D patterns, the structuration becomes more challenging and requires several complex and expensive patterning processes such as gray-scale electron beam lithography, laser ablation, focused ion beam lithography, two photon polymerization and dry etching techniques.

In this work, we propose a straightforward technique for realizing 3D structuration intended for silicon based materials (Si, SiN, SiOCH …). This structuration technique is based on ion implantation and selective wet etching .

In a first step a pattern is performed by lithography on a substrate, then ion implantation is performed through the resist mask in order to create localized modifications in the material, thus the pattern is transferred into the subjacent layer. Finally, after the resist stripping, a selective wet etching is carried out to remove selectively the modified material regarding the non-modified one. The type of implanted ions and wet etching baths depend on the morphology of the substrate.

In this study we have demonstrated the feasibility of this new 3D structuration process on Silicon and SiOCH. The mechanisms understanding involved during both implantation and wet etching processes will be presented through characterizations by photoluminescence spectroscopy, Raman spectroscopy and Secondary Ion Mass Spectrometry (SIMS) for silicon samples, and ellipso-porosimetry, Fourier Transform InfraRed spectroscopy (FTIR) for SiOCH samples.

11:00am **NS-MoM9 Design and Realization of 3D Printed AFM Probes**, *N. Alsharif, A. Burkatovsky, C. Lissandrello, A.E. White,* ***Keith Brown****,* Boston University

Atomic force microscopy (AFM) is an enabling tool for nanoscience due to its ability to image surfaces with sub-nanometer resolution. One drawback, however, is that the AFM probe must be chosen to complement the material properties of the system of interest – *e.g*. stiff probes are ideal for imaging hard surfaces while soft probes are needed for softer biological materials. Furthermore, the conventional lithography techniques that are used to fabricate AFM probes can only generate limited architectures from a narrow subset of materials. In analogy to the impact rapid prototyping has made on macroscopic manufacturing, nanoscale 3D printing can in principle be used to construct AFM probes in a manner that allows important properties such as spring constant and vibrational resonance frequency to be rationally chosen. Moreover, since it is possible to fully control the 3D structure of a probe, additional properties such as higher harmonic resonance frequencies and deflection sensitivity can be independently adjusted. Here, we demonstrate that functioning AFM cantilevers that are compatible with commercial AFM systems can be 3D printed and used for imaging. In particular, a series of bisegmented probes with consistent spring constants but different resonance frequencies were designed, printed, and evaluated using an AFM. Their properties were found to be consistent with finite element mechanical simulations and comparable to commercially available probes. In addition, we found that the second harmonic mode could be tuned to an integer multiple of the principle harmonic, in a manner that could provide multimode imaging with resonance enhancement. This work opens the door for complex non-rectilinear cantilevers that provide uniquely tuned force-distance relationships or harmonic behavior.

11:20am **NS-MoM10 Evaluating the Reproducibility of Atomically Precise Dopant Structures**, *J. Koepke, D. Scrymgeour, R.J. Simonson, M. Marshall,* Sandia National Laboratories; *J. Owen,* Zyvex Labs; *D. Ward, R. Muller, M. Carroll, S. Misra,* ***Ezra Bussmann****,* Sandia National Laboratories

Moore's law extrapolates to microelectronic devices with atomic size features around 2020 [1]. Anticipating engineering of nanoelectronics at this scale, techniques to tune dopant profiles in silicon have evolved to the ultimate limit of single-atom control. A single atom transistor [2], a device with just one P dopant atom placed in the channel with atomic selectivity, was recently fabricated via hydrogen resist scanning tunneling microscopy (STM) lithography. Despite the promise of atomically precise dopant placement, there are significant challenges to fabrication based on STM lithography such as scale-up, robustness, yield, and reproducibility.

This talk describes techniques to evaluate and optimize the yield and reproducibility of patterning and incorporation for single dopant placement. The hydrogen resist STM lithography method uses electrons from the STM tip to selectively desorb hydrogen atoms from the Si(100) – 2×1:H surface. Dosing the sample with PH_3 and annealing selectively incorporates P dopants into the regions patterned with the STM tip. The key challenges for fabricating the dopant arrays are alignment of the STM tip to the dimer rows of the Si(100) surface, choice of lithographic window size and patterning conditions, and identification of the incorporated dopant after dosing and annealing the sample. Scaling the arrays to larger sizes requires reproducible STM tips that pattern consistently and very low alignment error. Using the precise alignment of the STM tip to the dimer rows of Si(100) surface, we have improved lithography yield for patterning windows for single dopant incorporation from 10% to 40%. We have developed image analysis capability to rapidly identify the dopant atoms in order to verify the results of the array fabrication and provide feedback to the lithography and dosing conditions for process optimization. Comparing results of dopant incorporation with modeling enables fine tuning of the PH_3 dosing and incorporation conditions to improve the single dopant yield.

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Data collected using a ZyVector™ STM Lithography Control System from Zyvex Labs.

[1] International Technology Roadmap for Semiconductors, http://www.itrs2.net/.

[2] Fueschle, *et al*., *Nat. Nano*. **7**(4), 242 (2012).

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