Electronic Materials and Photonics Division
Room 101A - Session EM+MP+PS-MoM

IoT Session: CMOS, Beyond the Roadmap and Over the Cliff

Moderators: Sean King, Intel Corporation, Wilman Tsai, Taiwan Semiconductor Manufacturing Company (TSMC)

8:20am **EM+MP+PS-MoM1 Aluminum Gettering Gate for Improving Defect Density in SiGe MOSCAP Devices**, ***Emily Thomson***, *M. Kavrik, A.C. Kummel,* University of California at San Diego

The use of SiGe alloys in place of silicon in semiconductor devices has been anticipated for many years due to its high carrier mobility and tunability of the band gap by varying Ge content. However, widespread use of SiGe in industry has been prevented by the presence of interface defects between the SiGe and oxide layer in MOSCAP devices. It has been shown that Ge-Ox bonds at the interface are the main source of these defects so by encouraging SiOx bonds or discouraging GeOx bonds, interface defects can be minimized. The higher heat of formation of SiOx compared with GeOx allows for the selective destruction of GeOx bonds using an oxygen scavenging metal as the gate metal, causing oxygen from GeOx bonds to diffuse through the oxide layer. Here, aluminum was used as an oxygen scavenging gate in order to achieve a low defect density of 3E11 $eV^{-1}cm^{-2}$. The high-k dielectric HfO_2 was deposited using atomic layer deposition with precursors TDMAH (tetrakis (dimethylamido) hafnium) and H2O and the aluminum gates were deposited using thermal evaporation. MOSCAP devices with nickel gates were fabricated and measured in parallel to show contrast with a non-scavenging gate metal. C-V measurements were used to characterize interface defect density. TEM images confirmed oxygen scavenging by showing a silicon rich SiGe-oxide interface and an Al2O3 layer at the HfO2-Al gate interface.

8:40am **EM+MP+PS-MoM2 Direct Growth of Single Crystal Compound Semiconductor Materials on Diverse Substrates for Beyond the Roadmap Multifunctional Integrated Circuits**, ***Debarghya Sarkar***, *R. Kapadia,* University of Southern California

Technological advancement in semiconductor devices for the past several decades has been mainly driven by scaling device dimensions to achieve high computational density and thus operational bandwidth. The next generation of technological advancement is likely to come from vertical fine-grain integration of multiple materials for 3D multifunctional integrated circuits. Epitaxial lift-off and transfer processes are currently employed towards realizing such structures, which though successful, have several shortcomings. On the other hand, direct growth of technologically relevant materials on amorphous dielectrics using state-of-the-art vapor-phase crystal growth techniques results in polycrystalline films with uncontrolled morphology unsuitable for high performance devices. As a potential solution addressing these issues, here we report the recent advances made in the templated liquid phase (TLP) growth technique that enables growth of large-area single crystals of compound semiconductors directly on diverse non-epitaxial substrates. We demonstrate growth of optoelectronic materials such as binary III-V InP and InAs, and optical bandgap tuning with ternary III-V materials like InGaP. We also show phase-controlled growth of binary IV-V materials such as Sn_4P_3 and SnP for high capacity anode materials in Li and Na ion batteries. Further, as the first step towards directly integrating multiple materials on the same substrate, we demonstrate atomically-sharp lateral heterojunctions of cubic InP and rhombohedral Sn_4P_3 crystals. We grow these materials in selective area with deterministic template geometry and conformal to underlying device nanostructures on any thermally stable crystalline (Gd_2O_3), amorphous (SiO_2, Si_3N_{-4}, TiO_2, and $Al_{-2}O_3$), or 2D (graphene) substrate. Despite grown on non-epitaxial substrates, the materials have been characterized to have high quality crystallinity, with high optoelectronic quantum yield irrespective of the substrate, and high carrier mobility. These demonstrations potentially mark the beginning of a new genre of material growth technique with increased opportunity for electronic, photonic, optoelectronic and energy devices, and system design with novel functionalities.

10:00am **EM+MP+PS-MoM6 Surface Free Energy and Interfacial Strain in HfO2 and HZO Ferroelectric Formation**, ***Andrew Kummel***, *E. Chagarov, M. Kavrik,* University of California at San Diego*; M. Katz, N. Sanford, A. Davydov,* National Institute of Standards and Technology (NIST)*; M. Lee,* National Taiwan University

The mechanism of stability of the phases of HfO_2, ZrO_2, and HZO ($Hf_xZr_{1-x}O_2$) were systematically investigated with density functional theory molecular dynamics (DFT-MD). For the bulk states, the monoclinic phase ("m") is about 80 mV per formula unit more stable than either the orthorhombic ferroelectric ("f") phase or tetragonal (t-phase) for all three oxides. The surface free energies of the (001), (110), and (111) surfaces of all three oxides were calculated using an identical DFT technique. For all three oxides, the (111) face has the lowest surface free energies consistent with experimental data on columnar HZO grains showing [111] is the preferred growth direction. However, the surface free energy for all direction are nearly degenerate between HfO_2, ZrO_2, and HZO; therefore, even for nanocrystal formation the surface free energy does not favor f-phase formation. The effect of stress/strain was calculated by determining the free energy of formation as a function of the volume of the unit cell. When the oxides are grown in the low density amorphous phase but a post deposition anneal is perform for crystallization. The crystalline forms are more dense than the amorphous forms and the DFT calculation show that a higher surface area per unit cells will greatly favor f-phase formation. However, the effect is nearly identical for HfO_2, ZrO_2, and HZO; this is consistent with experiments showing the molar volumes of HfO_2 and ZrO_2 being within 2%. Instead, formation of nanocrystalites is hypothesized to be the source of the enhanced processing window for HZO. Experimental data is consistent with partial phase separation in HZO. Atom probe tomography imaging of the chemical composition of TiN/5 nm HZO/Si(001) ferroelectric films show an asymmetric distribution of the Hf and Zr within the HZO layer with the Zr being concentrated near the TiN/HZO interface; this is consistent with ZrO_2 having a 100C lower crystallization temperature than HfO_2 and therefore initiate the crystallization starting on the TiN(111) surface. It is hypothesized that the nanocrystals which template on TiN(111) can produce the interfacial stress/strain needed to stabilize f-phase formation; high resolution TEM shows regions of epitaxial alignment between HZO and TiN consistent with this mechanism. In addition atom probe tomography (APT) was performed on TiN/HZO/Si structures to determine the film composition of the interfaces for indication of possible phase separation of HZO since phase separation could promote nanocrystal formation.

Funding by LAM Research is gratefully acknowledged

10:40am **EM+MP+PS-MoM8 The Role of Selective Processes in the Atomic Scale Era**, ***Robert Clark***, *J. Smith, K.-H. Yu, K. Tapily, G. Pattanaik, S. Consiglio, T. Hakamata, C.S. Wajda, A. Raley, G.J. Leusink,* TEL Technology Center, America, LLC **INVITED**

The semiconductor industry has reached the point where devices are approaching atomic scales. But continued scaling presents a number of new challenges to our industry. First, there is no longer plenty of room at the bottom, which has forced device makers to scale upward by adopting three dimensional device structures and architectures. This has resulted in a drastic increase in the aspect ratios encountered during chip manufacturing. In addition, even with the advent of EUV lithography it will be necessary to employ multi-patterning technologies in order to fabricate the sub-lithographic features necessary to scale further. Multi-patterning requires multiple masks per layer which presents a challenge in terms of aligning masks to each other within a layer, and from layer to layer as the chip is fabricated. Self-aligned process flows such as self-aligned blocks, fully self-aligned vias, and self-aligned contacts are being employed to increase the margin of allowable edge placement error (EPE) for aligning feature and layers to each other at the cost of additional process complexity as well as exacerbating the problem of ever-increasing aspect ratios. Finally, functional films at useful thicknesses need to be accommodated within the volume of the device without voids or seams that can impact chip yields through degraded electrical performance or by providing a source of particles or foreign material.

To overcome these difficulties it is necessary to begin transitioning from the current top down manufacturing paradigm to a bottom up or additive manufacturing style. Selective depositions and etches represent a path to make this transition for devices makers. Self-aligned process flows already make use of etch selectivity between materials in order to achieve feature self-alignment, but isotropic and anisotropic selective depositions can provide additional advantages. Because area selective depositions are

inherently self-aligned to the target material, they can enable new process flows for self-alignment. In addition, anisotropic feature filling can be used to fill high aspect ratio, or reentrant features on the chip without deleterious voids and seems as well as reducing the overburden needed for chemical mechanical polishing (CMP). And selective depositions can also be used to avoid or relieve the crowding of functional films within devices or other structures. In this presentation we seek to illustrate, with examples of new processes currently under investigation, how selective depositions and etches can enable future manufacturing nodes by introducing additive processing into the manufacturing flow.

11:20am **EM+MP+PS-MoM10 Selective Patterning of Silicon/Germanium Surfaces and Nanostructures via Surface Initiated Polymerization**, ***Amar Mohabir***, *T. Weiss, G. Tutuncuoglu, E.M. Vogel, M.A. Filler,* Georgia Institute of Technology

Functional devices (e.g., transistors) require controlled compositional heterogeneity and hierarchy at the nanoscale. When such devices are to be produced at very large throughputs (e.g., large-area integrated circuitry), an alternative to top-down patterning is necessary to define key features. Here, we show how surfaces exhibiting Si and Ge domains can be selectively masked using the surface-initiated growth of polymer films. Our approach is particularly useful for the patterning of, and subsequent deposition on, 3-D nanostructures, such as Si/Ge nanowire heterostructures. Such structures exhibit a variety of exposed facets that complicates direct (i.e., without a mask) area selective deposition approaches. Surface masking of Si, but not Ge, domains is accomplished by attaching an initiator to the surface followed by the atom transfer radical polymerization of polymethylmethacrylate (PMMA). Due to differences in initiator density on the Si and Ge regions, the resulting PMMA is approximately 2x thicker on the Si surface. A subsequent hydrogen peroxide etching step removes PMMA on the Ge surface, thus providing nearly 100% selectivity, but leaves the Si regions unaffected. We hypothesize the mechanism of PMMA removal is hydrogen peroxide diffusion through the polymer layer and etching of the underlying Ge atoms. In this study, we use a suite of spectroscopy and microscopy techniques to investigate the effect of initial Si/Ge surface treatment, PMMA polymerization conditions, and hydrogen peroxide etching conditions on the resulting polymer film properties and surface. The ability to selectively mask nanoscale objects in a bottom-up fashion opens up the possibility for nanoscale patterning in a simultaneously high-throughput and cost-effective manner.

11:40am **EM+MP+PS-MoM11 Chemically Selective Imaging of Sequential Infiltration Synthesis with nm-scale Spatial Resolution**, *D. Nowak,* ***Tom Albrecht***, Molecular Vista

Area selective deposition (ASD) is an active area of research for advanced nanofabrication. Closely related to ASD is sequential infiltration synthesis (SIS) where inorganic material is infused into select polymer material to render an organic/inorganic hybrid material based on a polymer-template. The organic component can be burned or etched away to leave only the inorganic component, which can be used as etch mask or for other purposes. For lithography applications, the length scale (in nanometers range) and the nature of material (organic and inorganic molecules) are such that traditional techniques such as FTIR, electron microscopy, and X-ray scattering are not able to yield real space, chemically selective imaging of SIS processes. Photo-induced Force Microscopy (PiFM) [1] combines infrared (IR) absorption spectroscopy and atomic force microscopy (AFM) via illumination of the tip-sample junction with tunable IR laser light and mechanical detection of forces acting on the tip in response to absorption of light by the sample. By mapping the IR absorption of the sample as a function of IR wavelength and position, nm-scale resolution is achieved in displaying the locations of heterogeneous materials on the surface of a sample. This imaging capability is useful for investigating chemical pre-patterns as well as selectively deposited materials in area-selective processes like block copolymer directed self-assembly, SIS [2], and a variety of area-selective deposition techniques. In this talk, we will present the PiFM results on a model system: Al_2O_3 SIS using trimethyl aluminum and H_2O with poly(styrene-block-methyl methacrylate) (PS-*b*-PMMA) block copolymer with 41 nm full pitch lamellae, demonstrating sub-10 nm spatial resolution of chemically selective imaging.

[1] D. Nowak et al., Sci. Adv. **2**, e150157 (2016).

[2] Y. Tseng et al., J. Mater. Chem. **21**, 11722(2011).

Materials and Processes for Quantum Computing Focus Topic

Room 203A - Session MP+EM+MN+NS-MoM

Systems and Devices for Quantum Computing I

Moderator: Vivekananda Adiga, IBM, T.J. Watson Research Center

9:00am **MP+EM+MN+NS-MoM3 Quantum Supremacy: Checking a Quantum Computer with a Classical Supercomputer**, ***John Martinis***, Google Inc **INVITED**

As microelectronics technology nears the end of exponential growth over time, known as Moore's law, there is a renewed interest in new computing paradigms such as quantum computing. A key step in the roadmap to build a scientifically or commercially useful quantum computer will be to demonstrate its exponentially growing computing power. I will explain how a 7 by 7 array of superconducting xmon qubits with nearest-neighbor coupling, and with programmable single- and two-qubit gate with errors of about 0.2%, can execute a modest depth quantum computation that fully entangles the 49 qubits. Sampling of the resulting output can be checked against a classical simulation to demonstrate proper operation of the quantum computer and compare its system error rate with predictions. With a computation space of 2^49 = 5 x 10^14 states, the quantum computation can only be checked using the biggest supercomputers. I will show experimental data towards this demonstration from a 9 qubit adjustable-coupler "gmon" device, which implements the basic sampling algorithm of quantum supremacy for a computational (Hilbert) space of about 500. We have begun testing of the quantum supremacy chip.

9:40am **MP+EM+MN+NS-MoM5 Active Protection of a Superconducting Qubit against Josephson Amplifier Backaction**, ***Baleegh Abdo***, *N.T. Bronn, O. Jinka, S.B. Olivadese, A. Corcoles, M. Brink,* IBM T. J. Watson Research Center*; R. Lake, D.P. Pappas,* National Institute of Standards and Technology*; J.M. Chow,* IBM T. J. Watson Research Center

Nonreciprocal microwave devices, e.g., isolators and circulators, are key components in high-fidelity, quantum-nondemolition (QND), measurement schemes. They separate input from output and protect the quantum systems from unwanted backaction originated by the output chain. However, state-of-the-art, cryogenic circulators and isolators are disadvantageous in scalable architectures because they are lossy, bulky and use magnetic materials and strong magnetic fields, which are not compatible with superconducting circuits. In this work, we realize and characterize nonreciprocal, superconducting devices suitable for qubit readout, which are formed by coupling two nondegenerate Josephson mixers in interferometric schemes. Nonreciprocity is generated by applying a phase gradient between the same-frequency pumps feeding the devices, which play the role of the magnetic field in a Faraday medium. We incorporate these Josephson-based, nonreciprocal devices into a qubit setup and demonstrate fast, high-fidelity, QND measurements of the qubit while actively protecting it against Josephson amplifier backaction.

10:00am **MP+EM+MN+NS-MoM6 Nonlinear Light-matter Interaction: From Superconducting Qubits to Spins in Diamond**, ***Eyal Buks***, Israel Institute of Technology, Israel

Cavity quantum electrodynamics (CQED) is the study of the interaction between matter and photons confined in a cavity. In the Jaynes-Cummings model the matter is described using the two-level approximation, and only a single cavity mode is taken into account. The interaction has a relatively large effect when the ratio $E/\hbar\omega$ between the energy gap E separating the two levels and the cavity mode photon energy $\hbar\omega$ is tuned close to unity.

The talk is devoted to the study of the light-matter interaction in the nonlinear regime using three different CQED systems. In the first experiment a Josephson flux qubit serves as a two-level system and a superconducting resonator as the cavity [1]. We experimentally find that the cavity response exhibits higher order resonances (called superharmonic resonances) in the nonlinear regime when the ratio $E/\hbar\omega$ is tuned close to an integer value larger than unity. In the second experiment the interaction between a spin ensemble of diphenylpicrylhydrazyl (DPPH) molecules and a superconducting resonator is explored in the region where $E/\hbar\omega \gg 1$ [2]. We find that the cavity response is significantly modified when the spins are intensively driven close to their Larmor frequency. Retardation in the response of the spin ensemble gives rise to effects such as cavity mode cooling and heating. In the third experiment the interaction between localized spins in diamond (nitrogen-vacancy and nitrogen substitutional) and a superconducting resonator is studied [3]. We find that nonlinearity

imposes a fundamental limit upon sensitivity of CQED-based spin detection.

References

1. Eyal Buks, Chunqing Deng, Jean-Luc F.X. Orgazzi, Martin Otto and Adrian Lupascu, Phys. Rev. A 94, 033807 (2016).

2. Hui Wang, Sergei Masis, Roei Levi, Oleg Shtempluk and Eyal Buks, Phys. Rev. A 95, 053853 (2017).

3. Nir Alfasi, Sergei Masis, Roni Winik, Demitry Farfurnik, Oleg Shtempluck, Nir Bar-Gill and Eyal Buks, arXiv:1711.07760.

10:40am **MP+EM+MN+NS-MoM8 Variations in Surface Dipole-Moment Density with Coverage for C/Au(110) – (2 × 1) and Electroplated Au Ion-trap Electrodes**, ***Dustin Hite**, K.S. McKay,* National Institute of Standards and Technology (NIST)*; H.Z. Jooya,* ITAMP, Harvard-Smithsonian Center for Astrophysics*; E. Kim,* University of Nevada, Las Vegas*; P.F. Weck,* Sandia National Laboratories*; H.R. Sadeghpour,* ITAMP, Harvard-Smithsonian Center for Astrophysics*; D.P. Pappas,* National Institute of Standards and Technology (NIST)

Ion traps, designed to test the feasibility of scalable quantum information processing, suffer from excessive electric-field noise that increases strongly as the ion-electrode spacing decreases in progressively smaller traps. This noise couples to the charge of the ions in the trap causing motional heating, which can result in the decoherence of quantum logic gates. This heating can be reduced by orders of magnitude with the use of cryogenic trap electrodes or by in-situ surface cleaning with ion bombardment in traps with room-temperature electrodes. Many experiments over the past two decades have supported theories that model this noise source as being caused by fluctuations in the dipole moments of contaminant adsorbates on the metallic trap electrode surfaces. Gold electrodes are often used to avoid oxidation and other contaminants, nevertheless a thin carbonaceous layer of approximately 3 monolayers (ML) develops on Au, even due to air exposure alone. In this work, we have studied the model system of C/Au(110) – (2 × 1) to understand the mechanisms for the variations in the surface dipole-moment density as a function of the degree of carbon coverage. We have implemented Kelvin probe force microscopy, along with x-ray photoelectron spectroscopy, to determine an average dipole-moment density with increasing carbon coverage, and have compared the results to density functional theory aided by ab-initio molecular dynamics techniques. We find a nearly linear decrease in the work function with a rate of approximately -0.7 eV/ML for sub-monolayer coverages, a regime in which trapped ions have been observed to have a maximum rate of heating. Finally, we compare the results for the model system to those for a microfabricated ion-trap chip with electroplated Au electrodes contaminated with a native hydrocarbon layer incrementally removed by ion bombardment.

11:00am **MP+EM+MN+NS-MoM9 A Compact Cryogenic Setup for Quantum Computing with Trapped Atomic Ions**, ***Ismail Inlek**, R. Spivey, G. Vrijsen, Z. Jia, J. Kim,* Duke University

Trapped atomic ions are standard qubits for quantum computing with their long coherence times and high-fidelity qubit operations for universal quantum logic gates. However, conventional trapped ion systems often utilize bulky vacuum and optics setups, hindering scalability and ease of use. We aim to address these infrastructure issues by packaging micro-fabricated ion traps in an ultra-high vacuum (UHV) environment and designing optics to be an integral part of the overall system. Additionally, small footprint of the sealed UHV package allows users to easily install it on a cryostat to benefit from lower heating rates and further reduced vacuum levels. Moreover, these ion trap packages can be conveniently swapped to benefit from micro-fabricated ion trap manufacturing improvements without external UHV maintenance requirements. Towards achieving this goal, we report successful ion trapping in a compact cryogenic setup and characterize the performance of our apparatus for quantum computing applications.

11:20am **MP+EM+MN+NS-MoM10 Advances in Trapped Ion Quantum Computing**, ***Jungsang Kim,*** Duke University **INVITED**

Trapped ions provide a highly desirable physical substrate on which to construct a scalable quantum computer. All qubits are exactly identical by nature, can be well isolated from the environment to establish long coherence times, and high fidelity quantum logic gates have been readily available. Furthermore, the long-range Coulomb interactions used for multi-qubit gates in a chain allows for highly connected network of qubits that are fully programmable, opening up opportunities for advanced and flexible quantum computer architectures. Some of the most advanced and complex quantum algorithms have been implemented in trapped ion systems leveraging these features. On the other hand, the ion trap systems so far have mainly relied upon conventional methodology used in atomic physics labs to set up the lasers, vacuum chambers and their optical alignments to realize the system. Novel integration technologies, including micro-fabrication, micro-electromechanical system (MEMS), and advanced packaging approaches have been adopted in the past decade to push the integration level for trapped ion systems. In this presentation, I will summarize the state-of-the-art systems used to implement quantum computing applications in the laboratories today, and also outline system design approach currently undertaken to improve the stability, reliability, and programmability of trapped ion quantum computers. Then, I will discuss the opportunities and challenges ahead for reaching a scalable quantum computer capable of executing useful tasks.

Nanometer-scale Science and Technology Division
Room 102B - Session NS+2D+AN+EM+MN+MP+PC+RM-MoM

IoT Session: Nanostructured Devices and Sensors

Moderators: David Czaplewski, Argonne National Laboratory, Liya Yu, NIST Center for Nanoscale Science and Technology

8:20am **NS+2D+AN+EM+MN+MP+PC+RM-MoM1 Integrating Nanodiamonds with Augmented Artificial Intelligence and Digital Health to Optimize Combination Therapy**, ***Dean Ho,*** UCLA **INVITED**

Dean Ho, Ph.D.

Nanodiamonds have emerged as promising candidates for clinical drug delivery due to their ability to carry a wide range of candidate therapies, unique surface properties, and biological tolerability. This lecture will highlight our recent clinical trial to validate a nanodiamond-embedded biomaterial for root canal therapy indications [1]. We will discuss the broad spectrum of efficacy, safety, characterization, and other studies that bridged in vitro with preclinical and downstream in-human studies. This lecture will also discuss upcoming clinical nanodiamond-based drug carrier studies, as well as our work in augmented artificial intelligence (AI) to develop globally optimized nanodiamond-modified therapy. Pairing nanodiamond platforms with augmented AI will lead to major advances in drug development and markedly improve response rates and treatment outcomes for a broad spectrum of disorders. Our recent clinical trials using these powerful combination therapy optimization technologies and digital health platforms to scale their implementation to usher in a new era of nanomedicine-based treatment will also be discussed [2].

1. Lee et al., Proceedings of the National Academy of Sciences, 2017

2. Zarrinpar et al., Science Translational Medicine, 2016

9:00am **NS+2D+AN+EM+MN+MP+PC+RM-MoM3 Morphology-Controlled Large-Scale Tin Oxide Nanostructures for Highly Sensitive Room Temperature Gas Sensor**, ***Amrit Sharma,*** Norfolk State University

Highly sensitive large-scale tin oxide (SnO_2) nanostructures were grown on a glass substrate by vapor-liquid-solid (VLS) process using a mixture of anhydrous tin (II) chloride ($SnCl_2$) and zinc chloride ($ZnCl_2$) powders. We demonstrate a new kind of single cell vapor deposition system to precisely control nanostructural morphology by changing the weight ratio of $SnCl_2$ and $ZnCl_2$ and growth temperature. The morphology and structural property of as-grown nanostructures were characterized using scanning electron microscopy (SEM) and X-ray diffraction (XRD). The SEM images revealed that the SnO_2 nanostructures with different densities, sizes, and shapes can be achieved by adjusting the weight ratio of $SnCl_2$ and $ZnCl_2$. SnO_2 nanostructures with diameter ~20 nm and length ~100 nm showed ~85% sensitivity and 53 seconds of response time, whereas the nanorods with diameter ~100 nm and length ~ 1mm showed ~50% sensitivity with 198 seconds response time. The nanostructured material with small size and shape showed better sensitivity on sensing at room temperature compared to previously reported SnO_2 based sensors.

9:20am **NS+2D+AN+EM+MN+MP+PC+RM-MoM4 Improving the Localized Surface Plasmonic Resonance Sensing Properties by Composite Metal/Dielectric Mixtures**, ***Steven Larson*[1]*, Y. Zhao,*** University of Georgia

Localized surface plasmon resonance (LSPR)-based sensors, whose resonance absorbance wavelength responds to the change in the local dielectric environment have attracted great attention and have been

[1] **NSTD Student Award Finalist**

widely studied over the past decade. These sensors are traditionally improved by modifying the shape, size, and gap in the plasmonic nanostructure of the sensor. The sensitivity can also be tuned by the dielectric constant of the plasmonic material, such as noble metal alloys, but the improvements are not significant. Here we show that using a metal-dielectric composite, one can significantly improve the sensitivity of a LSPR sensor. Regular nanotriangle pattern samples composed of a mixture of Ag and MgF_2 with different composition ratios are prepared by combining nanosphere lithography and electron beam co-deposition. The plasmon resonance of these composite nanostructures at high Ag composition (C_{Ag})are shown to redshift with C_{Ag} until a composition threshold ($C_{Ag} \leq 90\%$) is met, where the resonance wavelength is nearly constant, slightly blue shifting. Multiple morphological and compositional characterization techniques are used to confirm that the shifts in the plasmonic properties are due to the change in composition and not a change in the morphology. The resulting LSPR sensor at C_{Ag} = 90 at.% can achieve a sensitivity of 696 RIU/nm, as compared to 312 RIU/nm for the same nanotriangle with pure Ag. This significantly improved sensitivity is due to the modified dispersion relationship of the dielectric constant by the composite and will play an important role in future plasmonic material design and applications.

9:40am **NS+2D+AN+EM+MN+MP+PC+RM-MoM5 Improving the Selectivity of Tin (IV) Oxide Paper Based Gas Sensors with Plasma Surface Modification***, **Kimberly Hiyoto**, E.R. Fisher,* Colorado State University

Metal oxide nanomaterials are desirable for solid-state gas sensors because of their ability to detect a wide variety of gases through changes in resistance resulting from gas-surface interactions. When optimizing these sensors, the supporting substrate is rarely considered, resulting in devices that are often brittle and have a fixed amount of nanomaterial that can be exposed to target analytes. Recent work using paper as the supporting substrate yields more affordable sensors that are flexible, allowing for a more robust device. Furthermore, the porous morphology of the paper also provides a larger surface area to attach metal oxides when compared to a traditional flat substrate of the same dimensions. Another limitation of these metal oxide sensors is inherent in the detection method. The lack of selectivity and required operating temperature of ≥300 °C limits the widespread use of metal oxide sensors. Dopants or the addition of a filter in the device design are typical approaches to address these problems; however, this increases fabrication complexity and cost. Plasma processing is a promising strategy to address these issues because it maintains desirable bulk properties but modifies the surface of the material to enhance gas sensor performance.

Here, we describe the Ar/O_2 plasma modification of paper based, tin (IV) oxide (SnO_2) nanoparticle devices as a function of applied rf power and precursor pressure. After plasma modification, the paper-based sensors exhibited improved response to carbon dioxide, ethanol, and benzene when compared to the untreated material on a more traditional substrate, zirconium dioxide. Additionally, sensor response to a target gas changed depending on the plasma modification parameters used, indicating the selectivity of these SnO_2 sensors can be easily tailored via plasma processing. Response and recovery studies of both the treated and untreated sensors will be discussed to demonstrate the dynamic behavior of these devices to the target gases as another measure of gas sensor performance and durability. Along with sensing behavior, optical emission spectroscopy and X-ray photoelectron spectroscopy provide insight into how the plasma modified the material, ultimately elucidating the relationship between material surface chemistry and sensor selectivity. Finally, preliminary work using this same fabrication process with another type of metal oxide gas sensor will be discussed to demonstrate the applicability of this method for other types of materials. Ultimately, these data work toward improved understanding of the gas sensing mechanism to design better performing gas sensors.

10:00am **NS+2D+AN+EM+MN+MP+PC+RM-MoM6 TiN@Si_3N_4 Core-shell Heterostructures as Nanoantennas for Photocatalytic Reforming of Methanol***, **Alejandro Alvarez Barragan**, L. Mangolini,* University of California, Riverside

The light-harvesting capacity of plasmonic nanoparticles has recently garnered attention in the synthesis of nanoantennas for photocatalysis. Aluminum, gold, and silver have been used to successfully drive hydrogen dissociation and CO oxidation reactions by injecting hot electrons into chemically active catalysts —such as platinum and palladium— adsorbed to their surface. However, the low response of aluminum at visible-near infrared (vis-NIR) wavelengths, the high cost of silver and gold, and the low thermal stability of these three metals, inspire the quest for alternative plasmonic materials that could potentially expand the field towards more ambitious and cost-effective applications. Titanium nitride (TiN) is a conductive ceramic with high hardness and bulk melting point (2930 °C). Its plasmon resonance located in the vis-NIR region, low cost relative to gold and silver, and well-understood properties as a thin film in the semiconductor industry, make it a strong alternative to mainstream plasmonic metals. The present work encompasses a comprehensive study of the oxidation kinetics of TiN particles at the nanoscale and an exploration of its role as nanoantennas for light-induced methanol reformation. TiN particles are synthesized via a scalable, modular, non-thermal plasma method. Titanium and nitrogen precursors are transported into a RF frequency plasma where TiN particles nucleate and grow. The high surface area and nitrogen deficiency of the particles facilitate the oxidation of the material and weaken its plasmonic response. The introduction of a secondary reactor with an input of SiH_4 as precursor gas leads to the formation of a Si_3N_4 coating. STEM and XPS analyses show that Si_3N_4 acts as a diffusion barrier, dramatically reducing the oxidation of the ~8 nm TiN particles. UV-vis-NIR spectrophotometry data show that the core-shell heterostructures experience a substantial blue-shift of the plasmon peak and an increase in intensity compared to the bare TiN. Platinum nanoparticles were subsequently deposited on the TiN@Si_3N_4 by photo-induced reduction of an aqueous solution of chlorplatinic acid. After rinsing and centrifuging, the Pt/TiN@Si_3N_4 heterostructures were diluted in a 50:50 water/methanol solution. Upon photoexcitation via white light illumination, hydrogen generation was readily detected by gas chromatography. This work also highlights the wide range of applications available for light-induced processes, ranging from materials processing (deposition of Pt particles) to photocatalysis (methanol reforming). It also strengthens the case for alternative plasmonic materials in a field dominated by precious metals.

10:40am **NS+2D+AN+EM+MN+MP+PC+RM-MoM8 Nanostructured Sensor and Device Applications of Infiltrated Zinc Oxide***, **Leonidas Ocola**,* Argonne National Laboratory*; Y. Wang, J. Chen,* University of Wisconsin-Milwaukee*; P. Blaisdell-Pijuan,* California State University-Fullerton*; R. Divan,* Argonne National Laboratory **INVITED**

With the increased portfolio of materials deposited using atomic layer deposition (ALD) there has been an increased interest in infiltrated metal oxides such as zinc oxide for novel applications. We find that ZnO metal oxide ALD infiltration can be useful for nanoscale resolution imaging of biological samples and to fabricate novel UV and gas nanosensors with high sensitivity. The ALD infiltration utilizes similar concepts of the ALD coating process with the significant difference in process exposure times, pressure, and purpose. The purpose is to allow the precursor gases infiltrate a porous media (such as a dry biological sample or a photoresist polymer) and allow the reaction to occur inside the material matrix.

In terms of device fabrication we use SU8 as a negative resist that allows for localization of the infiltration process. We have used this property to make a device that is UV sensitive, and that is sensitive to ppm concentrations of gases by using infiltrated zinc oxide. The large bandgap and semiconductor properties of ZnO allow for a visible-blind ultra violet light sensor. We used a standard UV flashlight that emits at 408 nm as the UV source. We also tested the same device for sensing gases like nitrous oxide and formaldehyde. We show that the device can detect these gases with concentrations of 5 ppm. The change in current for such low concentrations was measured to be between 25% and 35 %.

With the purpose of investigating quantum applications of infiltrated ZnO, we also have characterized the growth of ZnO in PS-b-PMMA block copolymers (BCP) of spherical and cylindrical sub-20 nm morphologies and studied how the photoluminescence of these nanostructures varies per its seed layer. We report blue-shifted photoemission at 335nm (3.70eV), suggesting quantum confinement effects. Samples of ZnO prepared with an alumina seed layer showed additional defect state photoemission at 470nm and 520nm for spherical and cylindrical BCP morphologies, respectively. Defect photoemission was not observed in samples prepared without a seed layer. No Raman peaks were observed for any samples with less than four cycles of ZnO, implying the absence of phonons and the functionality of these ZnO nanostructures as isolated emitters. To that effect we have demonstrated a fabrication path to isolate single infiltrated cylinders, paving the way for further studies of optical properties of individual 20 nm ZnO nanostructures.

- Use of the Center for Nanoscale Materials an Office of Science user facility, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

11:20am **NS+2D+AN+EM+MN+MP+PC+RM-MoM10 Templates for the Investigation of Size-Selected Nanocluster Networks***, Patrick Edwards, V.V. Kresin,* University of Southern California

The study of metal nanoclusters has revealed quantum nanoscale effects unique to the fully size-resolved regime. A highly notable example is electronic shell structure, akin to that in atoms and nuclei, which arises when confined conduction electrons organize into discrete energy levels. One consequence is the possibility of dramatic enhancement in electron Cooper pairing. Recent research from our group has provided evidence of this enhancement in certain free Al nanoclusters, with the electronic transition taking place at a temperature two orders of magnitude above that of bulk aluminum. We now aim to take advantage of this phenomenon by exploring the pairing transition in size-selected nanoclusters soft-landed on an appropriate substrate. Of particular interest are graphene and nanotube device architectures which provide unique templates for organizing nanocluster arrays. For example, a network of such superconducting nanoislands may induce superconductivity in graphene even at low coverages. Theory also predicts that an array of nanoclusters will not only support, but even enhance the Josephson current by 2-3 orders of magnitude. Carbon allotropes offer two distinct advantages for our system. First, the weak out-of-plane bonding provides a surface with less potential to disturb the structure of the soft-landed nanoclusters. Second, the tunability of graphene and carbon nanotube-based field effect transistors offers a versatile probe of nanocluster properties. We are also investigating the use of biological nanowires (bacterial flagella) as potential scaffolds upon which to deposit such nanocluster networks. These abundant and naturally occurring nanowires could serve as low cost and highly reproducible alternatives to the more common metallic or semiconductor templates.

Research supported by the Army Research Office (W911NF-17-1-0154).

11:40am **NS+2D+AN+EM+MN+MP+PC+RM-MoM11 High Performance Detection for X-ray and g -ray with $MAPbX_3$ Perovskite Single Crystals***, X. Wang, Z. Zhu, Q. Li, J. Wu, X. Zhang, B. Wang,* ***Wei Lei,*** Southeast University

Recently, organometallic lead trihalide perovskites have emerged as a new generation of opto-electronic materials. However, the high performance detection for x-ray and gamma-ray with $MAPbX_3$ is still a big challenge. For x-ray and gamma-ray detections, the detectors should have high sensitivity. If the photon counting method is adopted, the high energy resolution and high time resolution are also required. In this work, the large area $MAPbBr_3$ single crystal has been fabricated with a facile methodology. Due to the quite thick active material and large carrier mobility, the x-ray photons and gamma-ray photons can be absorbed with high efficiency. The photo generated electrons and holes can also be collected effectively with the large electric field. To decrease the dark current in the detection, a novel photo-diode structure is proposed here. In crystallization process of $MAPbI_3$ single crystal, the p-n junction can be formed with doping of selenium atoms into $MAPbI_3$ single crystal.

With various temperature method, the 30mm×30mm×7mm $MAPbBr_3$ single perovskite crystal is fabricated. As the experimental results shown, almost all of the 100 keV x-ray photons are absorbed when the $MAPbBr_3$ SPC is 7mm thick. The detection sensitivity is as high as 305 μC $Gy_{air}^{-1}cm^{-2}$when the anode voltage of x-ray tube is 30 kV .

To reduce the dark current in the detection, two type of photo diode structures have been proposed here. Firstly, a photo diode with structure of Au/TPD/$MAPbBr_3$ PSC/C_{60}/PCBM/Ag has been fabricated with spin coating and sputtering methods. Although the dark current density can be reduced to 20 nA/cm^2 with -30V bias voltage, the temporal response time is nearly 50 μs due to the defects on the interfaces between PSC and carriers transport layers. Then, by doping selenium (Se) in $MAPbI_3$ perovskite single crystals (DPC) crystallization process, low dark current p-n junctions were fabricated without any organic layers. This photodiodes gives the high detection sensitivity as 21000 mC $Gy_{air}^{-1}cm^{-2}$ and 41 mC $Gy_{air}^{-1}cm^{-2}$ for 60 keV x-ray and 1.33 MeV gamma-ray respectively. In this photodiode, the transition time becomes shorter under higher electric field, and the carrier lifetime also becomes shorter due to the dopant of Se atoms. Finally, the temporal response time is measured as 3 μs by experiments. The FWHM width of energy spectrum is decreased to 3.2%@1330 keV.

Materials and Processes for Quantum Computing Focus Topic

Room 203A - Session MP+AM+EM+NS-MoA

Systems and Devices for Quantum Computing II

Moderator: Josh Mutus, Google Inc

1:20pm **MP+AM+EM+NS-MoA1 Quantum Engineering of Superconducting Qubits*, William Oliver,*** MIT Lincoln Laboratory **INVITED**

Superconducting qubits are coherent artificial atoms assembled from electrical circuit elements and microwave optical components. Their lithographic scalability, compatibility with microwave control, and operability at nanosecond time scales all converge to make the superconducting qubit a highly attractive candidate for the constituent logical elements of a quantum information processor. Over the past decade, spectacular improvement in the manufacturing and control of these devices has moved superconducting qubits from the realm of scientific curiosity to the threshold of technical reality. In this talk, we review this progress and our own work at MIT that are creating a future of engineered quantum systems.

2:00pm **MP+AM+EM+NS-MoA3 The Quantum Socket: A Wiring Method for Superconducting Quantum Computing*, Matteo Mariantoni,*** University of Waterloo, Canada **INVITED**

I will provide a brief introduction to the main technological and scientific challenges to be faced in order to build a practical quantum computer, with emphasis on the case of superconducting quantum computing. I will then delve into a detailed explanation of a method to address the wiring of a two-dimensional array of superconducting quantum bit (qubits): The quantum socket [1]. Next, I will show how the quantum socket can be extended to a medium-scale quantum computer and how it can help mitigate coherent leakage errors due to qubits interacting with spurious cavity modes [2]. I will then show thermocompression bonding technology [3], a method that allows us to further protect qubits from the environment. In particular, I will propose a new qubit design based on our experimental implementation of thermocompression bonded chips, where vacuum gap capacitors are used to reduce dissipation due to so-called two-level state defects in amorphous dielectrics, which are the insulators presently use in our qubits.

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[3] C.R.H. McRae, J. H. Béjanin, Z. Pagel, A.O. Abdallah, T.G. McConkey, C.T. Earnest, J.R. Rinehart, and **M. Mariantoni**, Thermocompression Bonding Technology for Multilayer Superconducting Quantum Circuits, Appl. Phys. Lett. **111**, 123501 (2017)

3:00pm **MP+AM+EM+NS-MoA6 50 Ohm Superconducting Kinetic Inductance Traveling-Wave Amplifier with flexible pump frequency for Four Wave Mixing and Three Wave Mixing*, Xian Wu,*** *M. Bal, J. Long, H.S. Ku, R. Lake, D.P. Pappas,* National Institute of Standards and Technology

We developed a 50 Ohm transmission-line based superconducting kinetic inductance traveling-wave (KIT) amplifier using high inductance material NbTiN. The nonlinearity originates from the kinetic inductance of the superconductor and enables amplification. Often, the impedance of the transmission line is significantly higher than the 50 Ohm microwave environment due to the dominance of kinetic inductance over geometric inductance at micron size scales. To address this impedance mismatch, we engineered “fingers” on each side of the original coplanar waveguide KIT [1] to introduce extra capacitance that decreases the impedance to approximately 50 Ohm [2,3]. Those extra “fingers” also function to create a band stop at higher frequency to bend the dispersion relation between wave vector (k) and frequency (f), which allows us to apply the pump frequency within a wide span of a few GHz and achieve several GHz gain bandwidth for chosen pump frequency. Another advantage of this structure is that it significantly reduces the phase velocity, hence shortening the physical length of this device. Gain measurements based on both four wave mixing and three wave mixing will be presented.

[1] Appl. Phys. Lett. **108**, 012601 (2016); https://doi.org/10.1063/1.4937922

[2] Journal of Applied Physics **119**, 083901 (2016); https://doi.org/10.1063/1.4942362

[3] Appl. Phys. Lett. **110**, 152601 (2017); https://doi.org/10.1063/1.4980102

3:40pm **MP+AM+EM+NS-MoA8 Near Term Development of Short Depth Quantum Processors*, J.M. Chow,*** IBM Research Division, T.J. Watson Research Center*; Martin Sandberg,* IBM, T.J. Watson Research Center **INVITED**

Quantum processors are currently in their infancy though the community is poised to explore bringing them to a state where they can outperform classical computations in relevant application. The challenges that lie ahead are plentiful and touch all aspects of the quantum computer, ranging from finding algorithms to building control software and control hardware as well as engineering and fabricating and testing the quantum hardware. In an effort to accelerate the development of quantum computing IBM launched the IBM Q experience. The Q Experience is a cloud-based platform which allows anyone to get familiar with quantum computing. It allows users to run experiments on actual quantum hardware.

In this talk I will focus on the development and characterization of short depth superconducting quantum hardware. Crosstalk and decoherence are some of the most pressing issues that we face today. Decoherence limits the number of operations that can be performed on the hardware (the depth of the circuit) whereas crosstalk can limit what operations can be performed in parallel on the circuit. The processors featured on the IBM Q experience are based on fixed frequency transmon qubits with a cross-resonance based two qubit gate. For this platform only a very narrow frequency range for the qubits is possible. This leads to problems related to frequency crowding and spurious interactions. Methods for characterizing and addressing both the frequency allocation and characterizing crosstalk will be discussed.

4:20pm **MP+AM+EM+NS-MoA10 Frequency Crowding in Lattices of Transmon Qubits*, S. Rosenblatt, Jared Hertzberg, J. Chavez-Garcia, N.T. Bronn, H. Paik, M.O. Sandberg, E. Magesan, J. Smolin, J.B. Yau, V.P. Adiga, M. Brink, J.M. Chow,*** IBM, T.J. Watson Research Center

A key goal in quantum computing is to develop scalable fault-tolerant quantum logic circuits. One promising architecture involves lattices of fixed-frequency transmon qubits coupled via cross-resonance gates. Fixed-frequency qubits offer high coherence and the all-microwave gate reduces circuit complexity. To optimize gate performance, excitation energies of neighboring qubits must be similar but non-degenerate. This architecture is thus sensitive to any variation in device parameters affecting transmon frequency. In this talk we will discuss a statistical model for the resulting ‘frequency crowding’ behavior, and suggest improvements in both architecture design and qubit fabrication in order to achieve scalable circuits with good gate fidelity.

*We acknowledge support from IARPA under Contract No. W911NF-16-0114.

Materials and Processes for Quantum Computing Focus Topic

Room 203A - Session MP+EM+NS-TuM

High Coherence Qubits for Quantum Computing

Moderator: Robert Ilic, National Institute of Standards and Technology

8:00am **MP+EM+NS-TuM1 MBE Grown Nitride Superconductors for Quantum Circuits**, ***Christopher Richardson***, *A. Alexander, C. Weddle,* Laboratory for Physical Sciences

Low microwave loss superconducting capacitors and inductors are critical circuit components of superconducting qubits. For transmon qubits, the ability to make high-quality planar resonators is an essential part of fabricating highly coherent qubits. Plasma assisted Molecular beam epitaxy (PAMBE) is used to grow niobium titanium nitride alloys ($Nb_xTi_{1-x}N$) directly on silicon (111) wafers. Using a structure first approach to design optimization, the structural, surface topology, chemical characteristics, and superconducting critical temperature of these films are used for optimization of the growth conditions before resonators are fabricated and tested. Here focus will be on the optimization of PAMBE-TiN films grown under slightly nitrogen rich conditions and high growth temperatures. Using films grown on high resistivity wafers, resonators are fabricated from coplanar waveguides with a narrow 6-µm wide center conductor and nominal 500-nm deep trench etch. Cryogenic testing at 100mK demonstrate low microwave loss that is evident from measured internal quality factors that are over 1M in the single photon regime and approach 10M at high powers. The motivation of using PAMBE to grow superconductors and the favorable comparison with resonators made from leading films synthesized with sputter deposition will also be discussed.

8:20am **MP+EM+NS-TuM2 Towards Improved Coherence Times in Transmon Qubits**, ***Sam Stanwyck***, Rigetti Computing

The depth of the circuit a quantum computer can perform depends directly on the coherence times of its qubits. There are many sources of decoherence in superconducting qubits, and identifying and minimizing dominant sources is a critical step in improving the performance of quantum computers. By measuring the internal quality factor of resonators and deliberately coupling to different loss mechanisms, we identify dominant sources of resonator loss in our systems, as well fabrication process changes to ameliorate these losses. Additionally, defects and materials present on the chip surface are correlated with process changes and coherence metrics.

8:40am **MP+EM+NS-TuM3 Design and Fabrication for High Coherence Quantum Circuits**, ***David Pappas***, *X. Wu, R. Lake, M. Bal, J. Long, C.R. McRae, H.S. Ku,* National Institute of Standards and Technology (NIST) **INVITED**

In this talk we focus on achieving high coherence in multi-component quantum circuits [1,13]. We will discuss geometric and electrical design strategies that mitigate energy loss while maintaining sufficient coupling to the qubit. Materials considerations -including dielectric losses in the substrate and various interfaces -play a central role in the implementation of these circuits. We will present a summary of our studies of the various participation factors and processing techniques to reduce dielectric loss in the capacitance of the qubits and resonators for readout and coupling. We also review our methods of integration for the key nonlinear component, the overlap tunnel junctions. In particular, techniques for achieving smooth surfaces for the junctions in a back-end process will be shown.

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9:20am **MP+EM+NS-TuM5 Effect of Surface Treatment on Superconducting Qubit Coherence**, ***Bradley Christensen***, University of Wisconsin-Madison; *P. Kumar,* University of Wisconsin - Madison; *J.J. Nelson, Y. Liu, A. Ballard, B.L.T. Plourde,* Syracuse University; *R. McDermott,* University of Wisconsin - Madison

Superconducting qubits are an attractive candidate for quantum information processing in the solid state . The fidelity of two-qubit gates for superconducting qubits is one of the more challenging limitations toward scalable quantum computing. A promising approach to perform these gates uses flux-tunable qubits to bias the qubit pairs into resonance to perform the necessary entangling operations. While this approach has many advantages over competing techniques, there are still significant issues that limit the fidelity of the gates. For example, since the two-qubit gate requires flux-biasing of a qubit, this also necessarily requires one of the qubits to operate at a flux-sensitive point, and as such, 1/f flux noise will restrict the possible gate fidelity. In addition to flux noise, flux-tunable qubits also suffer from microscopic two-level system (TLS) defects that reside in the high field areas on the qubit capacitor pad. These TLS cause an enhanced decay through both resonant interactions with the qubit and Landau-Zener transitions as the qubit frequency is biased through a TLS. While one could perform spectroscopy of the TLS to map out the inoperable space, this becomes an inefficient solution for large scale systems as the TLS resonance frequencies are not stable, and will significantly drift over time.

Recent experiments on SuperconductingQUantum Interference Devices (SQUID) point to adsorbed molecular O_2 as the dominant contributor to magnetism in superconducting thin films, and demonstrate that improvements in the sample vacuum environment lead to significant reductions in surface spin susceptibility and magnetic flux noise power. Furthermore, TLS defects have been shown to reside in surface oxides and interfaces, where the TLS dipole couples to the qubit electric field, and experiments on microwave resonators have shown that high-temperature annealing can yield a reduction in surface TLS defects.

Here, we present our results on improving the vacuum environment of superconducting qubits with an ultra-high vacuum (UHV) bake to remove the adsorbates. We measure flux noise power spectral densities (PSD) using Ramsey-based, CPMG filtering, and dressed-dephasing techniques, allowing the flux PSD measurements to span 10 decades. Furthermore, by measuring qubit lifetime as a function of frequency (swap spectroscopy), we can map out the coupling strength, lifetime, and density of the TLS defects. We present a comparison of treated and untreated devices to demonstrate the improvement to qubit coherence through a UHV bake.

9:40am **MP+EM+NS-TuM6 Metrology of Dielectric Loss using Lumped-Element Microwave Resonators**, ***Corey Rae McRae***, *X. Wu, M. Bal, J. Long, H.S. Ku, D.P. Pappas, R. Lake,* National Institute of Standards and Technology

Reducing the overall concentration of TLSs in dielectric materials remains at the forefront of materials research in quantum information science. In this work, we measure a lumped element resonator fabricated from a superconductor-dielectric-superconductor trilayer to determine the TLS loss of various dielectrics of interest in superconducting quantum computing. The deposition of the trilayer prior to fabrication allows control of the metal-dielectric interfaces, and the fabrication process is generalized so that resonators containing different dielectrics can be compared easily. This lithography method enables the measurement of trilayer capacitors and junctions that have been prepared entirely in situ in an ultrahigh vacuum environment. In future work, we will interrogate a new class of low-loss dielectrics grown with epitaxial methods using the measurement capabilities developed here.

11:00am **MP+EM+NS-TuM10 Direct Observation of Atomic Structure of Ultra Thin AlO_x Barriers in Al/AlO_x/Al Josephson Junctions for Quantum Devices**, ***Eva Olsson***, Chalmers University of Technology, Gothenburg, Sweden **INVITED**

The atomic structure of tunnel barriers in Josephson junctions for quantum devices and the corresponding interfaces determine the properties of the junction. The thinnest region in the barrier of a junction will be the preferential tunneling channel for charge carriers and the highest current. The current increases exponentially with decreasing barrier thickness. As a

consequence, a variation on the individual atom plane length scale results in inhomogeneity of the tunnel current across the barrier. There are several earlier experimental indirect indications that only a small fraction of the junction area is active.

We are using high resolution annular dark field (ADF) scanning transmission electron microscopy (STEM) imaging to obtain high resolution (better than 1 Å) and high precision (better than 1 pm) information about the local atomic structure [1]. We use ADF STEM imaging to directly determine the thickness distribution along the oxide barrier in Al/AlO_x/Al Josephson junctions [2]. The barrier thickness is about 1-2 nm. The thickness distribution shows that less than 10% of the junction area dominates the electron tunneling. We also study the influence of oxygen pressure and oxidation time on the thickness distribution. In addition, we determine the atomic structure and coordination of Al atoms within the oxide barrier layer using electron energy loss spectroscopy and nanobeam electron diffraction [3]. A lower Al coordination is observed at the metal/oxide interface compared to the interior of the oxide barrier. We also study the structure of the interfaces between the Al contact and the substrate [4,5].

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11:40am **MP+EM+NS-TuM12 Metrology of Tunnel Junctions for Superconducting Qubits**, ***Russell Lake***, National Institute of Standards and Technology (NIST); *X. Wu, H.S. Ku, J. Long, M. Bal, C.R. McRae,* National Institute of Standards and Technology (NIST) and University of Colorado Boulder; *D.P. Pappas,* National Institute of Standards and Technology (NIST)

Superconducting tunnel junctions make up the key non-linear circuit component in many implementations of quantum electrical circuits, including superconducting qubits. Therefore, controllable fabrication of superconducting junctions has taken a central role in the realization of quantum computers. In this talk we discuss fabrication and characterization of a wafer-scale process for nanoscale superconducting tunnel junctions (Al-AlOx-Al) [1]. We present the distribution of normal-state resistances across a wafer for different junction sizes. We have applied an analytical method of accounting for the current crowding in the junction leads [2] in order to give accurate predictions of the supercurrent from the room-temperature raw data. These corrected resistances can be input into the Ambegaokar-Baratoff formula to predict the critical current of the tunnel junctions in the superconducting state [3], and the corresponding non-linear effective inductance. These results are immediately relevant to the task of qubit frequency allocation in multi-qubit systems.

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[3] Phys. Rev. Lett. **10**, 486 (1963) and **11**, 104 (1963); https://doi.org/10.1103/PhysRevLett.10.486

Nanometer-scale Science and Technology Division
Room 102B - Session NS+AN+EM+MN+MP+RM-TuM

Nanophotonics, Plasmonics, and Metamaterials

Moderators: Alokik Kanwal, NIST Center for Nanoscale Science and Technology, Nikolai Klimov, National Institute of Standards and Technology

8:00am **NS+AN+EM+MN+MP+RM-TuM1 Parametric Nonlinear Interactions in Nanofabricated Silicon-based Photonics**, ***Amy Foster***, Johns Hopkins University **INVITED**

High optical confinement waveguides on integrated platforms enable nonlinear optical interactions with low power levels. The third-order nonlinear susceptibility, a modification of a material's permittivity due to an applied optical field, exists in all materials, and is an intensity-dependent process leading to third-order parametric effects. Harnessing the high optical intensities enabled by high confinement waveguides allows standard semiconductor materials to become power-efficient parametric nonlinear optical devices that can operate with powers in the mW range. The optical confinement of a waveguide also enables control over the waveguide's dispersion, allowing for phase-matching of the parametric processes thereby improving its operating bandwidth. Using standard nanofabrication techniques, integrated photonic devices can be tailored in both geometry at the nanoscale, and in magnitude of their third-order susceptibility through modification of their material properties. In this talk, we will discuss a variety of parametric nonlinear optical demonstrations in silicon-based waveguides including optical parametric amplification and oscillation, phase-sensitive amplification, and frequency conversion and comb generation. Furthermore, we will discuss these devices for a variety of applications including optical signal processing, spectroscopy, and security.

8:40am **NS+AN+EM+MN+MP+RM-TuM3 Ultrafast Optical Pulse Shaping using Dielectric Metasurfaces**, ***Amit Agrawal***, *S. Divitt, W. Zhu, C. Zhang, H.J. Lezec,* NIST Center for Nanoscale Science and Technology **INVITED**

Since the invention of femtosecond pulsed lasers, the field of ultrafast optical science and technology has seen significant progress in the generation and characterization of ultrashort optical pulses. Complimentary to development in generation and characterization techniques, arbitrary temporal shaping of optical pulses has become an integral part of the field. Fourier-transform pulse shaping is the most widely adopted approach that entails parallel modulation of spatially separated frequency components to achieve the desired pulse shape. Recently, dielectric metasurfaces have emerged as a powerful technology for arbitrary control over the amplitude, phase, or polarization of light in a single, compact optical element. Here, we experimentally demonstrate shaping of sub-10 fsec ultrafast optical pulses using a centimeter-scale silicon metasurface acting as both amplitude and phase modulation mask. The deep-subwavelength silicon nanostructures, positioned with nanometer precision, are individual optimized to provide accurate amplitude and phase modulations to each frequency component. Masks of this type offer a lower cost, larger size, higher resolution, high diffraction efficiency, high damage threshold method for controlling ultrafast pulses.

9:20am **NS+AN+EM+MN+MP+RM-TuM5 Single-Particle Nanophotonics and Materials Investigations with Optical Microresonator Spectrometers**, ***Erik Horak***, University of Wisconsin - Madison; *K.D. Heylman, K.A. Knapper, M.T. Rea, F. Pan, L.T. Hogan, R.H. Goldsmith,* University of Wisconsin-Madison **INVITED**

Optical microresonators have achieved impressive sensitivities in a range of experimental modalities. We leverage the exquisite sensitivity of microresonators to enable highly sensitive spectroscopic characterization of objects on the surface of the resonator. In this way, not only can single particles be detected and identified, but fundamental properties of interrogated systems can be studied, opening a path to mechanistic studies and label-free chemical identification.

Our photothermal-based technique employs a two-beam geometry. A fiber-coupled (probe) beam records the whispering-gallery mode (WGM) resonance wavelength via evanescent coupling through a tapered fiber, while a second free-space (pump) beam heats absorbing particles or molecules on the surface of the microresonator, shifting the WGM resonance. In essence we use the microresonator as a nearfield thermometer to measure dissipated heat upon optical excitation. To circumvent the photothermal background of the popular SiO_2 on Si toroidal resonators, we have developed an all-SiO_2 microtoroidal resonator, unlocking visible wavelengths to interrogation. We further employed a double-modulation technique through simultaneous Pound-Drever-Hall locking of the probe beam and amplitude modulation of the pump beam to reach sub-100 Hz or single attometer resonance shift resolution. This corresponds to signals much smaller than that predicted from a single-molecule, and thus represents an avenue toward single-molecule absorption spectroscopy.

We demonstrate this technique by examining gold nanorods (AuNR), which validate our experimental setup with near-diffraction limited photothermal maps, Lorentzian absorption spectra with stochastic center wavelengths, and single dipole polarization dependences. Further, AuNRs in close proximity to microresonator WGMs display signatures of photonic-plasmonic interactions, a forest of Fano resonances decorating the plasmonic absorption feature. This platform offers a facile methodology to study these complex interactions, with thermal annealing of the AuNRs producing highly controllable tuning of Fano resonances. Applying our platform to conductive polymers (CP), we have begun to understand the

fundamental properties that enable the high conductivity from a bottom-up nanoscale perspective. We examine the interplay between homogeneous and heterogeneous broadening, measure the long-range ordering, and determine relative surface orientation of CPs. These examples firmly demonstrate the utility of our platform to go beyond sensing allowing exploration of novel characteristics in complex systems and potentially the observation of chemical and biochemical dynamics.

11:00am **NS+AN+EM+MN+MP+RM-TuM10 Optomechanical Interactions for Metrology and Signal Processing***, **Karen Grutter**,* The Laboratory for Physical Sciences **INVITED**

Imprinting radio-frequency (RF) signals on optical carriers has a broad range of applications from metrology to communication and has been accomplished in bulk components using a variety of techniques. Achieving this functionality on a chip could broaden the potential application space, but the bulk frequency generation methods do not translate directly to the nanoscale. A number of methods have been proposed for on-chip frequency generation, including various sources of electro-optic modulation, comb generation via material nonlinearities in microresonators, and optomechanical/opto-acoustic interactions. In this talk, we will discuss the features of these sources, with particular focus on optomechanical interactions.

One potential phenomenon enabling opto-acoustic frequency generation is stimulated Brillouin scattering (SBS), which is essentially an interaction between propagating phonons and photons. This effect has been demonstrated in optical fibers, and recent results in on-chip waveguides show promise. One of the challenges with SBS on chip is that gain is dependent on long interaction lengths.

This interaction can be enhanced by moving to a different domain of phonon/photon interaction: cavity optomechanics. In an optomechanical cavity, the characteristics of the generated frequency are dependent on the mechanical eigenmode. We will demonstrate the relationship between mechanical quality factor and phase noise in ring optomechanical oscillators.

The optomechanical interaction can be optimized beyond that of ring resonators by further confining optical and mechanical modes using photonic and phononic crystals. We have designed and fabricated Si_3N_4 nanobeam optomechanical crystals with ~4 GHz mechanical breathing modes. The increased optomechanical coupling of these nanobeams confers high sensitivity to displacement, which could be exploited for various metrology applications, which we will discuss.

Further enhancement of the optomechanical coupling can be achieved by modifying the optomechanical crystal geometry to support an optical slot mode. We have designed and fabricated ~3 GHz-frequency slot-mode optomechanical crystals in Si_3N_4. In addition to increasing the optomechanical coupling compared to the single-nanobeam device, this structure has increased versatility, enabling interaction with other stimuli and modalities. We have integrated NEMS actuators with a slot-mode optomechanical crystal, and used these actuators to tune the optical mode and lock it to an external, fixed laser wavelength. This increases the practicality of this device, enabling longer-term measurements and stabler frequency sources.

11:40am **NS+AN+EM+MN+MP+RM-TuM12 Cold-atom based Sensors and Standards***, **Stephen Eckel**, D.S. Barker, J.A. Fedchak, N.N. Klimov, E. Norrgard, J. Scherschligt,* National Institute of Standards and Technology **INVITED**

In this talk, I will describe our recent efforts to merge nanophotonics, ultra-high vacuum, and atomic physics together to build a new generation of cold atom sensors and standards. In particular, I will focus on our recent realization of a single-beam system for cooling lithium atoms, an atomic species recently identified as an excellent candidate for a primary vacuum standard. Our system uses a triangular-shaped nanofabricated diffraction grating to produce the necessary beams for a magneto-optical trap that cools and slows the atoms. Unlike systems that use rubidium or cesium, which can be loaded from a vapor, lithium introduces additional complications because it must be produce from a thermal source requiring loading of the magneto-optical trap from behind the chip. Finally, I will conclude by talking about other trap geometries that we are pursuing, how they benefit vacuum and inertial sensors, and what the synergy of integrated nanophotonics, high-vacuum and atomic physics might be able to bring.

Electronic Materials and Photonics Division
Room 101A - Session EM+2D+AN+MI+MP+NS-TuA

Solar/Energy Harvesting and Quantum Materials and Applications

Moderators: Yohannes Abate, Georgia State University, Nicholas Strandwitz, Lehigh University

2:20pm **EM+2D+AN+MI+MP+NS-TuA1 Plasmonic Metasurface Electrodes for Excitonic Solar Cells.**, ***Deirdre O'Carroll,*** Rutgers, the State University of New Jersey **INVITED**

Excitonic organic solar cell technologies, while not currently competitive with inorganic-semiconductor analogues, can exhibit very small device embodied energies (due to comparatively low temperature and low energy-use fabrication processes), which is of interest for minimizing overall device cost and energy-payback time. To improve energy conversion efficiency in thin-film excitonic organic solar cells, light management using nanophotonic structures is necessary. Here, our recent work on improving light trapping in deeply-subwavelength excitonic organic semiconductor films using plasmonic metasurfaces will be presented. Numerous exciton-metasurface interaction phenomena, such as absorption-induced scattering, exciton-plasmon coupling and morphology-dependent surface plasmon light-trapping are observed to give rise to improved light trapping at different regions of the solar spectrum. Additionally, an approach to achieve the theoretical limits to the efficiency of excitonic organic photovoltaics (~22%) will be proposed that involves control of radiative recombination rate, and optimization of both photoluminescence quantum efficiency and photon recycling in organic semiconductor thin-films.

3:00pm **EM+2D+AN+MI+MP+NS-TuA3 Photoemission Electron Microscopy as a New Tool to Study the Electronic Properties of an Inhomogeneous Semiconductor for Photovoltaics**, *M. Berg,* Sandia National Laboratories*; J. Kephart, A. Munshi, W.S. Sampath,* Colorado State University*;* ***Taisuke Ohta****, C. Chan,* Sandia National Laboratories

The energy positions of the valence and conduction electronic states with respect to the vacuum level are essential parameters to evaluate how the band gaps of semiconductors or Fermi-levels of metals line up with respect to each other. Such electronic structures of materials can be determined using photoemission spectroscopy (PES). PES measurements, however, remain challenging for inhomogeneous materials with nano- to micrometer lateral dimensions due to its mesoscopic probing area, typically no less than several microns. Photoemission electron microscopy (PEEM) is a cathode lens electron microscopy technique that combines photoemission imaging with spectroscopic modes of operation to provide PES spectra from areas less than one micron in size. Here, we present PEEM studies of the electronic structure of polycrystalline cadmium telluride (CdTe) thin films, a test case to examine the applicability of this new microscopic approach to photovoltaic materials. Post-deposition $CdCl_2$ treatment of CdTe is known to increase photovoltaic efficiency. However, the precise chemical, structural, and electronic changes that underpin this improvement are still debated. In this study, PEEM was used to spatially map the vacuum level and ionization energy of CdTe films, enabling the identification of electronic structure variations between grains and grain boundaries. *In vacuo* preparation and inert environment transfer of oxide-free CdTe surfaces isolated the separate effects of $CdCl_2$ treatment and ambient oxygen exposure. Qualitatively, grain boundaries displayed lower work function and downward band bending relative to grain interiors, but only after air exposure of $CdCl_2$-treated CdTe. This study highlights the importance of probing the spatially varying electronic structure, elucidating the concurrent impacts of processing steps ($CdCl_2$ treatment and oxygen exposure) to develop a comprehensive picture of local electronic structure in an inhomogeneous semiconductor.

The PEEM work was performed at the Center for Integrated Nanotechnologies, an Office of Science User Facility (DE-AC04-94AL85000). M. B. & C. C. were supported by a U.S. DOE-EERE SunShot BRIDGE award (DE-FOA-0000654 CPS25859). T. O. was supported by the CINT user program and Sandia LDRD. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. The views expressed in the article do not necessarily represent the views of the US DOE or the US Government.

3:20pm **EM+2D+AN+MI+MP+NS-TuA4 Modification of Bandgap for Lead-Free Double Perovskite $Cs_2AgInCl_6$ with Bi Doping**, ***Hassan Siddique****, H. Da, X.Q. Wang, R.C. Dai, Z.P. Wang, Z.J. Ding, Z.M. Zhang,* University of Science and Technology of China

Lead halide perovskites have the excellent luminescent properties but exist some vital disadvantages such as instability and Pb toxicity. Lead-free double perovskites draw attention due to a possible candidate for environment-friendly materials. Direct bandgap lead-free halide of $Cs_2AgInCl_6$ is one of them. [1] In this work Bi doping $Cs_2AgInCl_6$ (CAIC) was successfully prepared. Bi dopant above 15% CAIC can restrict the parity forbidden transition responding to sub absorption peak around 600 nm.[2] On the other hand, the intensity of photoluminescence enhances with the increasing Bi dopant and touches the maximum around 30% doping, then gradually loses its intensity with further doping due to the mechanism of the concentration quenching at room temperature. Bi doping in CAIC can also modify the band gap. The absorption spectra indicate that the band gap reduces from 3.10eV without Bi doping to 2.68eV for $Cs_2AgIn_{0.30}Bi_{0.70}Cl_6$. PL decay life time reveals the good intrinsic excitonic feature with less defect trappers [3]. Average life time for $Cs_2AgIn_{0.70}Bi_{0.30}Cl_6$ is 490 ns which is least among all other $Cs_2AgIn_{(1-x)}Bi_xCl_6$ doping. Thermogravimetric analysis (TGA) result reveals thermal stability of $Cs_2AgIn_{0.30}Bi_{0.70}Cl_6$ for the high-temperature 506°C. The Bi doping can decrease the band gap, restrict defect states, enhance PL and improve stability; these good performances make $Cs_2AgIn_{(1-x)}Bi_xCl_6$ more suitable for optoelectronic properties.

4:20pm **EM+2D+AN+MI+MP+NS-TuA7 Optimized (Quantum) Photonics**, ***Jelena Vuckovic,*** Stanford University **INVITED**

Photonics has numerous applications ranging from optical interconnects, classical and quantum computing, to sensing (such as LIDAR and AR), and imaging. However, the state of the art photonics is bulky, inefficient, sensitive to environment, lossy, and its performance is severely degraded in real-world environment as opposed to ideal laboratory conditions, which has prevented from using it in many practical applications. Therefore, it is clear that new approaches for implementing photonics are crucial.

We have recently developed a computational approach to inverse-design photonics based on desired performance, with fabrication constraints and structure robustness incorporated in design process [1,2]. Our approach performs physics guided search through the full parameter space until the optimal solution is reached. Resulting device designs are non-intuitive (see Figure), but are fabricable using standard techniques, resistant to temperature variations of hundreds of degrees, typical fabrication errors, and they outperform state of the art counterparts by many orders of magnitude in footprint, efficiency and stability. This is completely different from conventional approach to design photonics, which is almost always performed by brute-force or intuition-guided tuning of a few parameters of known structures, until satisfactory performance is achieved, and which almost always leads to sub-optimal designs.

Apart from integrated photonics, our approach is also applicable to any other optical and quantum optical devices and systems. In recent years, color centers in diamond and silicon carbide (SiC) have emerged as a possible platform for implementation of quantum circuits [3,4]. We demonstrate how such quantum hardware can also be optimized to be robust, efficient, and scalable.

References

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5:00pm **EM+2D+AN+MI+MP+NS-TuA9 Optical Properties of Single Silicon Vacancies in 4H-SiC**, *H.B. Banks,* National Research Council Postdoc residing at the Naval Research Laboratory*; O. Soykal,* Sotera Defense Solutions, Inc, residing at the Naval Research Laboratory*; S.P. Pavunny, R.L. Myers-Ward, D.K. Gaskill,* ***Samuel Carter****,* U.S. Naval Research Laboratory

Defects in wide bandgap materials have generated substantial interest as promising systems for quantum information and quantum sensing due to bright, stable optical emission that is often coupled to long-lived spin states. One promising defect system is the silicon monovacancy in SiC (V_{Si}), which has a spin-3/2 ground state that can be optically polarized and maintain long spin coherence times even at room temperature. SiC is an attractive material in terms of mature growth and fabrication technology

and also has a low natural abundance of nuclear spins, which reduces spin dephasing. While significant work has been performed to study the spin properties of V_{Si} for ensembles and even single defects, the optical properties and their connection to the spin system are less developed. Here we report on high resolution optical spectroscopy of single V_{Si} defects, specifically V2 defects, at low temperatures. Using laser excitation spectroscopy, the zero phonon line (ZPL) transitions corresponding to the m_s=±1/2 and m_s=±3/2 spin states are resolved, with a linewidth down to 70 MHz and a splitting of 1 GHz. While there is significant variation in the transition energies from one defect to another, the splitting of these lines is very uniform. We also find that emission from the V2 defect under resonant excitation of these lines rapidly decays on two very different timescales. Slow decay on a 10 ms timescale is attributed to photoionization of V_{Si} and can be prevented by periodically exciting the defect with a second laser at 745 nm. Fast decay on a µs or shorter time scale occurs due to a combination of intersystem crossing and spin polarization of the ground state. A significant difference in the decay rates of the two transitions is observed, which gives rise to spin-dependent photoluminescence intensity and non-resonant optical spin polarization. These results further our understanding of the connection between the optical and spin properties of this defect system that are necessary to optically control and readout the spin system as well as to develop a spin-photon quantum interface.

5:20pm **EM+2D+AN+MI+MP+NS-TuA10 Photoluminescence Studies on Patterned Silicon Vacancy Defects in Li Ion Implanted 4H-SiC for Scalable Quantum Device Applications**, ***Shojan Pavunny,*** U. S. Naval Research Laboratory*; S.G. Carter, H.B. Banks, R.L. Myers-Ward, P. Klein,* U.S. Naval Research Laboratory*; E.S. Bielejec,* Sandia National Laboratories*; M.T. DeJarld, A.S. Bracker, E.R. Glaser, D.K. Gaskill,* U.S. Naval Research Laboratory

Recently, silicon vacancy defect centers (V_{Si}) in the CMOS compatible wide bandgap semiconductor SiC hexagonal polytypes have drawn great research interest for future applications in scalable quantum information and quantum sensing mainly due to their high electronic spin (S = 3/2) with a long coherence time at room temperature. Realization of future densely integrated quantum devices will greatly benefit from the ability to deterministically induce the desired V_{Si} density at the optimal location in the three-dimensional solid-state matrix with nanometer accuracy and excellent optical properties. With this motivation, we demonstrate targeted formation of arrays of V_{Si} ensembles as well as single defects in high-quality 4H-SiC epilayers by a direct, maskless focused ion beam implantation technique with a designed lateral separation of ~5 µm and a ~25 nm spot size. We have carried out high-resolution optical spectroscopy studies (E⊥c and E ∥c) on these arrays, in which lithium ions are implanted at doses varying from 10^{12} – 10^{15} Li/cm^2 at a fixed energy of 100 keV to a depth of ~400 nm from the surface. Photoluminescence intensity and defect conversion yield with dose, photostability, fluorescence saturation, and V_1:V_1' intensity evolutions with temperature and excitation power were investigated. Results obtained from temperature dependent photoluminescence studies can provide key insights in the design and fabrication of scalable and reproducible three dimensional SiC quantum hybrid devices including photonic crystal cavities.

5:40pm **EM+2D+AN+MI+MP+NS-TuA11 Processing of Cavities in SiC Material for Quantum Technologies**, ***Rachael Myers-Ward,*** *K. Hobart, K.M. Daniels, A.J. Giles, M.J. Tadjer, L.E. Luna, F.J. Kub, S.P. Pavunny, S.G. Carter, H.B. Banks, E.R. Glaser,* U.S. Naval Research Laboratory*; P.B. Klein,* Sotera Defense Solutions*; K. Qiao, Y. Kim, J. Kim,* Massachusetts Institute of Technology*; D.K. Gaskill,* U.S. Naval Research Laboratory

Silicon carbide is a material of interest for quantum computing and sensing applications owing to deep point defect centers with long spin coherence times (which characterizes the lifetime of the qubit), specifically the V_{Si} [1], divacancies [2] and nitrogen-vacancy centers [3]. These spin qubits have been isolated and coherently controlled, where V_{Si} have T_2 coherence times up to 100 µs [4] and divacancies to 1 ms [2], making these two defects of most interest to date. While the current spin coherence times have been shown to be as long as 1 ms, further improvements are needed to fully realize the potential of SiC for quantum applications. In this work, we create V_{Si} in epitaxial SiC and investigate fabricating the layers into microstructures suitable for using the V_{Si} photoluminescence (PL) emission. We have found 4H-SiC epitaxial layers grown under standard growth conditions and with varying doping densities from 10^{14} to 10^{18} cm^{-3} have no measureable V_{Si} present, as determined by confocal PL. To introduce V_{Si}, we used 2 MeV electron irradiation in doses ranging from 0.75 to 75 kGy. This results in V_{Si} PL ranging from single to ensemble emission within the confocal volume. Hence, we are able to tune the vacancy concentration.

In order to improve the indistinguishable photons from the V_{Si} and/or divacancies for real applications, photonic crystal cavities (PCC) are used to tune the emission energy [4]. Our PCC design consists of a planar array of cylindrical holes approximately 220 nm wide in a slab of SiC, ~300-500 nm thin having an area 50 x 50 µm^2, similar to [4]. To maximize the PCC quality factor, the slab should have a large index of refraction difference on the top and bottom; i.e., an air gap is desired under the slab. To achieve this goal, we have identified four fabrication methods to create the PCC. One of these techniques is to use remote epitaxy as an innovative approach which entails growing epitaxial graphene on a SiC substrate by means of Si sublimation. Silicon carbide is then grown on a monolayer of graphene to the desired film thickness [5]. This thin SiC layer is then transferred, facilitated by the weak van der Waal forces at the graphene/SiC substrate interface, to a substrate more amenable to cavity fabrication. All four fabrication methods will be presented in detail.

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6:00pm **EM+2D+AN+MI+MP+NS-TuA12 Investigation of Localized Electronic structures of PbSe Quantum Dot Superlattice on a Highly Oriented Pyrolytic Graphite (HOPG)**, ***Il Jo Kwak,*** *S. Ueda,* University of California at San Diego*; A. Abelson, C. Qian, M. Law,* University of California, Irvine*; A.C. Kummel,* University of California at San Diego

Lead-Chalcogenide quantum dots are of interest due to the facility of adjustment of their electrical and optical properties. Using a colloidal self-assembly technique, extended arrays of nanocrystal QDs superlattices can be generated. The quantum confinement within individual QDs in the superlattice is relaxed and delocalization of wave functions occurs due to coupling of the QDs. In the QD solids, bulk-like electronic bands with a bandwidth of 100~200 meV are expected to form which yield much higher carrier mobility and diffusion length compared to weakly-coupled QDs; however, the electronic properties of such highly ordered QD arrays are not fully understood. The local density of state of a highly ordered monolayer PdSe superlattice was investigated by low temperature scanning tunneling microscopy.

A monolayer of PbSe QDs was prepared using the Langmuir Schaefer deposition technique. First, oleate-capped PbSe QDs dispersed in hexane were drop casted onto diethylene glycol surface. After the hexane was evaporated, a (111) in-plane oriented polycrystalline FCC superlattice was formed on the diethylene glycol surface. NH_4SCN solution was applied onto the oleate-capped PbSe superlattice film. The injection of NH_4SCN initiates the ligand exchange and phase transformation from an FCC to a simple cubic structure superlattice. A monolayer QD superlattice was prepared on a HOPG substrate. Afterward, the HOPG sample was loaded into a commercial UHV scanning tunneling microscopy chamber with a base pressure of 1x10^{-10}torr. The sample was annealed to remove hydrocarbons and ligands from the surface. The topography of the QDs was observed with a tungsten tip. The STM images were acquired in constant current mode.

STM imaging showed the PbSe QD monolayer had 4-fold symmetry with an average inter QD spacing of 7nm. It is also found the height fluctuation of the QDs was 1nm indicating size variation of the QDs and imperfect crystal structure of the superlattice. Scanning tunneling spectroscopy was performed to investigate the electronic structure of the PdSe QDs using a variable z-mode with an external lock-in amplifier in the bias range of -2 to 2V. Single site STS showed resonant peaks from molecular orbitals of QDs before the ligand exchange process; however, the peaks were not observed after the ligand exchange due to necking between the QDs in the superlattice. In addition, the size of band gap was decreased as increasing the number of nearest neighboring QDs due to necking between QDs. Layer 2 QDs showed more p-type behavior than layer 1 QDs possibly due to the band bending effect at the interface of HOPG and QD superlattice.

Nanometer-scale Science and Technology Division
Room 203A - Session NS+2D+AN+MN+MP+SE-WeM

Micro, Nano and Opto Mechanics

Moderators: Robert Ilic, National Institute of Standards and Technology, Alokik Kanwal, NIST Center for Nanoscale Science and Technology

8:20am **NS+2D+AN+MN+MP+SE-WeM2 The Collective Behavior of Large Ensembles of Coupled MEMS Cantilevers with Varying Natural Frequencies**, ***Christopher Wallin***, National Institute of Standards and Technology, Center for Nanoscale Science and Technology; *N. Dick,* Tel Aviv University, Israel; *R. De Alba, D.A. Westly,* National Institute of Standards and Technology, Center for Nanoscale Science and Technology; *S. Grutzik,* Sandia National Laboratories; *A.T. Zehnder, R.H. Rand,* Cornell University; *V.A. Aksyuk,* National Institute of Standards and Technology, Center for Nanoscale Science and Technology; *S. Krylov,* Tel Aviv University, Israel; *B.R. Ilic,* National Institute of Standards and Technology, Center for Nanoscale Science and Technology

The collective behavior of nonlinear, coupled micro- and nano-electromechanical (M/NEMS) resonators has been shown to exhibit a host of nontrivial dynamics including abrupt pattern switching, multistability, hysteresis, intrinsically localized modes, and synchronization. Additionally, M/NEMS resonator arrays are extremely responsive to environmental perturbations making them excellent candidates for sensing applications when operated linearly. With our work, we investigate the collective dynamics of coplanar interdigitated arrays of prismatic microcantilevers operating in both the nonlinear and linear regimes.

Two opposing, partially interdigitated cantilever arrays with 100 cantilevers apiece were fabricated using a silicon–on–insulator wafer. The device consists of a unique geometry in which each array has cantilever lengths expanding linearly across the device in opposite directions giving a distribution of natural frequencies. The arrays were engineered to allow for large scale, nonlinear out-of-plane beam deflections through the removal of the entire silicon handle layer beneath the active array area.

For sufficiently large drive amplitudes, the resonators begin oscillating via combination parametric resonance (CPR) across the entire array. The CPR driven oscillations occur across a broad frequency band. The tunable coupling between nearest-neighbor cantilevers through fringing electrostatic fields provides a mechanism to vary the CPR response. Due to the sizable deflections, the device's nonlinearities are apparent including hysteresis effects. Our experimental results are supported and expanded by the development of a reduced order model based on the Galerkin decomposition which generates the leading features of our data including the CPR band.

When operating in the linear regime, the natural modes of the array have localized characteristics whereby a limited number of beams oscillate at each of the natural mode frequencies. Operating the device at higher harmonics increases mode separation as the propagation bands stretch. The distinct resonant peak separation coupled with the spatially confined modal response make higher harmonic operation of tailored, variable length cantilever arrays well suited for a variety of resonant based sensing applications.

8:40am **NS+2D+AN+MN+MP+SE-WeM3 Piezoelectric Optomechanical Systems**, ***Krishna Coimbatore Balram***, University of Bristol, UK **INVITED**

Nanoscale optomechanical systems, which rely on the strong interactions between co-localised optical and mechanical modes in nanoscale cavities, have been explored for a wide variety of applications ranging from sensing to signal transduction [Aspelmeyer et al., Rev. Mod. Phys. (2014)]. In this talk, I will discuss piezoelectric optomechanical platforms for efficient signal transduction between the radio frequency (RF) and optical domain. We use GaAs as our model platform (Balram et al., Optica (2014), Nature Photonics (2016), Phys. Rev. Applied (2017)) and discuss some of the research opportunities and challenges in this field, especially as we move towards higher mechanical frequencies (> 10 GHz).

9:20am **NS+2D+AN+MN+MP+SE-WeM5 Absolute Deflection Measurements in a MEMS/NEMS Fabry-Perot Interferometry System**, ***Roberto De Alba***, *C.B. Wallin, G. Holland,* National Institute of Standards and Technology; *S. Krylov,* Tel Aviv University, Israel; *B.R. Ilic,* National Institute of Standards and Technology

Micro- and nano-electromechanical systems (MEMS/NEMS) are among the most sensitive devices for detection of ultra-weak forces, masses, and displacements. The small scale of these structures affords them very high frequencies (MHz to GHz), high quality factors, rich nonlinear phenomena, and many other beneficial traits that make them ideal as sensors and testbeds of fundamental physics. Fabry-Perot laser interferometry is a widespread and robust technique for probing MEMS/NEMS devices because it is non-invasive and provides exceptional motion sensitivity (≈ 1 pm/Hz$^{1/2}$) from DC to roughly 100 MHz. This technique utilizes the silicon substrate beneath the MEMS/NEMS device as a static reference mirror; doing so provides common-mode noise rejection in contrast to interferometers that use an external reference mirror. Furthermore, this technique is compatible with a wide range of MEMS/NEMS materials, from common insulators and conductors to graphene and other atomically-thin membranes.

Despite the many strengths of this experimental technique, it suffers from two main drawbacks. Firstly, the measured signal becomes highly nonlinear for device displacements larger than λ/4, where λ is the laser wavelength. Secondly, because the silicon backplane is immovable, there is no simple or established technique for calibrating device motion. As such, published results utilizing this setup typically report deflection in "arbitrary units." In this work, we focus on fully characterizing the nonlinear aspects of a MEMS/NEMS Fabry-Perot interferometer and developing a generalized approach to calibrate device motion based the wavelength of light. We will demonstrate how to quickly and accurately determine both static and dynamic MEMS/NEMS deflection by measuring reflected laser power in the time domain. We will further show how a single calibration (made in the large-amplitude regime) can be applied to subsequent measurements taken at lower amplitudes as well as to measurements taken in the frequency domain (e.g. by a lock-in amplifier). Lastly, we will demonstrate the capability of imaging the first three vibrational modes of a MEMS cantilever by using a scanning laser.

9:40am **NS+2D+AN+MN+MP+SE-WeM6 Silicon on Insulator Electrostatically Actuated Bistable Cantilevers for Resonant Displacement/Acceleration Sensing**, *O. HaLevy, E. Benjamin, N. Krakover, Y. Kessler,* ***Slava Krylov***, Tel Aviv University, Israel

Resonant accelerometers incorporating vibrating beams demonstrate higher sensitivity and better robustness when compared to their statically operated counterparts. Electrostatic softening of the beams electrostatically coupled to the proof mass allows to enhance sensitivity of the resonant accelerometers. The displacement of the proof mass affects the gap between the mass and the beam and results in the beam's frequency change, which is maximal in the vicinity of the critical limit points of the voltage-deflection curve. The use of the snap-through buckling for this purpose is attractive since it is fully reversible and does not involve contact. While double-clamped curved bistable beams designed to demonstrate snap-through behavior can serve as resonant acceleration sensors [1], they suffer from high sensitivity to temperature and residual stress.

In this work we report on a design and fabrication of an electrostatically actuated bistable resonant cantilever [2], which demonstrates low sensitivity to the temperature and to the residual stress. The concept is based on the tailoring of the actuating force in such a way that the beam in its initial "as fabricated" configuration is positioned in the vicinity of the critical point. This is achieved by designing the actuating electrodes to be significantly thicker that the beam. Our reduced order (RO) Galerkin and coupled finite elements (FE) models results show that the frequency to deflection sensitivity of the L = 150 μm long, h = 16 μm wide and d = 1 μm thick cantilever can reach 20 Hz/nm. This is equivalent to the frequency to acceleration sensitivity of 388 Hz/g, obtained for the case of a 4 mm × 4 mm × 20 μm proof mass.

While the model results are promising, fabrication of the device incorporating the beams and the electrodes of the different thicknesses is challenging. We demonstrate fabrication of the 50 μm thick electrodes and ≈6 μm thick cantilevers from the same device layer of a Silicon on Insulator (SOI) wafer. Two-stage deep reactive ion etching (DRIE) process was used for an initial patterning of the electrodes and of the cantilever and for the thinning of the beams. We discuss the details of the fabrication process and preliminary experimental results.

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11:00am **NS+2D+AN+MN+MP+SE-WeM10 Electron-Photon-Phonon Hybrid Systems Based on Compound Semiconductor Mechanical Resonators**, ***Hiroshi Yamaguchi***, NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation, Japan **INVITED**

The use of compound semiconductor heterostructures as the elastic materials in the fabrication of micro/nanomechanical resonators has advantages, such like the improvement of mechanical properties through strain engineering, optomechanical transduction through carrier-mediated coupling, and piezoelectrically controllable nonlinearity [1]. The hybrid properties play the essential role in the operation where the different excitations of phonons, photons, and electrons are mutually interacted. In this invited talk, I will review our recent activities studying the electronic [2], photonic [3], and phononic [4] functions in GaAs-based mechanical resonators.

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11:40am **NS+2D+AN+MN+MP+SE-WeM12 Size Dependent Mechanics of Elastomers**, ***Le Li***, *N. Alsharif, K.A. Brown,* Boston University

Elastomers are fascinating materials owing to the fact that their mechanical properties are dictated by entropy. Due to their low modulus, chemical compatibility, and ease of processing, they are widely applied in fields from soft lithography to medical devices. While it is well accepted that they exhibit fascinating size-dependent mechanical properties when confined to thin films, the structure-property relationships that govern confined elastomers are difficult to unambiguously determine due to the mechanical influence of rigid support structures and unavoidable contributions from adhesion. As a result, a consensus regarding the moduli of elastomeric thin films has not emerged. Here, we present a combined computational and experimental approach to measure the true mechanical properties of thin elastomer films. First, we utilize extensive finite element simulations to determine a correction to the Hertzian contact model that depends upon a dimensionless film thickness and the polymer Poisson's ratio. In order to verify this correction, films composed of three different thermoplastics were studied using an atomic force microscopy (AFM) nanoindenting. Interestingly, all three were observed to soften when confined to films thinner than 100 nm, in agreement with literature reports of buckling experiments. To explore softer elastomeric materials that exhibit categorically different behavior, we extended this correction to the Johnson-Kendall-Roberts (JKR) model that considers adhesion in contact mechanics. Elastomer thin films with different crosslink densities were studied using AFM nanoindentation and finite element simulation to determine their moduli. We observed a drastic stiffening on all elastomeric films when they were confined to sub-micrometer thicknesses. More importantly, modulus of all sub-100 nm elastomer films converges to the same trend regardless of bulk crosslink density. We present a hypothesized molecular model explaining this behavior. These results shed new light on the nanomechanics of elastomers and provide a general process for exploring size-dependent mechanics in polymers.

Extending Additive Manufacturing to the Atomic Scale Focus Topic

Room 102B - Session AM+MP+NS-WeA

Atomic Scale Manipulation with SPM

Moderator: Sven Rogge, University of New South Wales, Australia

2:20pm **AM+MP+NS-WeA1 Advanced Scanning Probe Lithography: Processes, Nanopatterning and Nanoelectronics**, ***Ricardo Garcia,*** Inst Ciencia Materiales Madrid, CSIC, Spain **INVITED**

The nanoscale control afforded by scanning probe microscopes has prompted the development of a wide variety of scanning probe-based patterning methods. Some of these methods have demonstrated a high degree of robustness and patterning capabilities that are unmatched by other lithographic techniques. However, the limited throughput of scanning probe lithography has prevented their exploitation in technological applications. Here, we review the fundamentals of scanning probe lithography and its use in materials science and nanotechnology. We introduce several methods, interactions and/or processes such as chemical, mechanical or thermal that enable the tip to modify surfaces. In particular, the presentation is focused on describing the fundamentals and applications of oxidation SPL for nanopatterning and device fabrication of nanoscale field-effect transistors, quantum dots, biosensors and molecular architectures involving a variety of systems from 2D materials to biomolecules; from self-assembled monolayers to silicon.

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-Y.K. Ryu, R. Garcia, Advanced oxidation scanning probe lithography. *Nanotechnology* **28**, 142003 (2017).

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3:00pm **AM+MP+NS-WeA3 Integrated Devices made Using Atomically Precise Advanced Manufacturing**, *D. Ward, D. Campbell, M. Marshall, T.-M. Lu, L. Tracy, L. Maurer, A. Baczweski,* ***Shashank Misra,*** Sandia National Laboratories

Atomically precise advanced manufacturing (APAM) has enjoyed considerable success in demonstrating high profile physics demonstrations, such as the single atom transistor. However, a considerably broader application space would open up if other transistor elements could be integrated with APAM devices, opening the door to high gain and room temperature operation. However, integration is generally limited by the high temperatures required to prepare pristine silicon substrates for APAM, and by the low temperatures at which phosphorus donors diffuse away once placed into silicon once APAM is complete. Here, we describe progress in integrating metal-dielectric surface gates to achieve high gain, and compensation doping to achieve room temperature operation. The Digital Electronics at the Atomic Limit (DEAL) project is supported by Sandia's Lab Directed Research and Development Program, and was performed in part at the Center for Integrated Nanotechnologies, a U.S. DOE Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

4:20pm **AM+MP+NS-WeA7 Electrical Transport Properties of Si:P δ-layer Devices**, ***Ranjit Kashid,*** *X. Wang, Namboodiri, J. Hagmann,* National Institute of Standards and Technology (NIST)*; S.W. Schmucker,* University of Maryland College Park*; J. Wyrick, C. Richter, R.M. Silver,* National Institute of Standards and Technology (NIST)

Si:P has been realized as one of the ideal systems for donor-based quantum computation. Site-selective doping of phosphorous atoms at the atomic scale using Scanning Tunneling Microscopy (STM) lithography on the Si(100) 2×1:H surface enables the fabrication of these devices. In the past, our group has demonstrated that degenerately doped & well confined Si:P monolayers can be fabricated using phosphine dosing and low-temperature Molecular Beam Epitaxy (MBE). In addition, a wide range of 1D and 2D nanoscale devices can be fabricated by combining STM lithography and low-temperature MBE. Here, we present magnetotransport and low-frequency 1/f noise measurements on degenerately doped 1D nanowires, 2D Hall Bars, and van der Pauw structures defined using STM lithography. Specifically, we investigate the dephasing mechanism and present a comparative analysis of transport between STM patterned and mesa etched Si:P δ-layer van der Pauw structures to further elucidate the effects of STM patterning on transport properties.

4:40pm **AM+MP+NS-WeA8 Atomically Precise Tip Positioning for Automated Writing of Atomic-scale Devices**, ***James Owen,*** *E. Fuchs, J.N. Randall, J.R. Von Ehr,* Zyvex Labs

Hydrogen depassivation lithography has enabled unprecedented sub-nanometer precision in the positioning of dopant atoms in silicon,[1] advancing the field of silicon quantum electronics. It has also been used for localised atomic layer deposition of Si [2] and TiO_2[3].

In pursuit of our overall vision of Atomically Precise Manufacturing, we are pursuing a number of tactics towards automated fabrication of atomically precise structures. STM lithography vectors are automatically aligned to the surface atomic lattice, and patterns can be input as geometric shapes or arbitrary bitmaps. To improve tip position precision, we have developed real-time creep and hysteresis error correction. Using this, we have previously demonstrated open-loop atomic precision patterning over length scales up to 100 nm. Above this scale, where hysteresis errors are more significant, we are able to reduce the position errors by ~90%.

In parallel with real-time position corrections, we have developed automatic fiducial alignment routines. The tip position can either be aligned to previously-drawn patterns or to deliberate fiducial marks. A large pattern can therefore be stitched together from write fields within which atomic precision can be obtained. Thus, precise patterning can be scaled to large areas.

In the burgeoning field of Quantum Metamaterials[4], large arrays of single dopant atoms are required, with extreme position precision and very high yield. However, the yield of the current thermal process for P limits the yield to 70%[5].

Based on recent work on removal of H from surface PH_2 species[6], we are developing a tip-assisted incorporation process, which prevents the recombination and desorption process. For this application, we need to write single-dimer patterns to adsorb only one PH_3 molecule. For these small patterns, Automated Feedback Controlled Lithography is used, so as to remove exactly the required H atoms from the surface. We are working to improve the detection of the H atom removal, using not only the spike in tunnel current but also the change in the local barrier height [7].

1. M. Fuechsle, et al. *Nat Nano* **7** 242-246 (2012) DOI:: 10.1038/nnano.2012.21

2. J. H. G. Owen et al., J. Vac. Sci. Technol. B **29**, 06F201 (2011).

3. J. B. Ballard, J. H. G. Owen, et al. *J. Vac. Sci. Technol. B*, **32**, 41804 (2014).

4. J. Salfi, et al. *Nat. Commun.*, **7**, 11342, (2016).

5. J. G. Keizer, S. Koelling, P. M. Koenraad, and M. Y. Simmons *ACS Nano***9** 12537-12541 (2015)

6. Q. Liu, Y. Lei, X. Shao, F. Ming, H. Xu, K. Wang, and X. Xiao, *Nanotechnology*, **27**(13), 135704, (2016).

7. F. Tajaddodianfar, S. O. R. Moheimani, J. Owen, and J. N. Randall, *Rev. Sci. Instrum.*, **89**(1), 13701, (2018)

5:00pm **AM+MP+NS-WeA9 Kilobyte Scale Data Storage through Autonomous Atom Assembly**, *A.F. Otte,* ***David Coffey,*** Delft University of Technology, Netherlands **INVITED**

The ability to manipulate individual atoms by means of scanning tunneling microscopy (STM) opens op opportunities for storage of digital data on the atomic scale. Recent achievements in this direction include data storage based on bits encoded in the charge state, the magnetic state, or the local presence of single atoms or atomic assemblies. However, a key challenge at this stage is the extension of such technologies into large-scale rewritable bit arrays. We demonstrate a digital atomic scale memory of up to 1 kilobyte (8,000 bits) using an array of individual surface vacancies in a chlorine terminated Cu(100) surface. The chlorine vacancies are found to be stable at temperatures up to 77 K. The memory, crafted using scanning tunneling microscopy at low temperature, can be read and re-written automatically by means of atomic scale markers, and offers an areal density of 502 Terabits per square inch, outperforming state-of-the-art hard disk drives by three orders of magnitude.

5:40pm **AM+MP+NS-WeA11 Extending the Capabilities of STM-based Dopant Device Fabrication**, *T. Skeren, N. Pascher, S.A. Köster,* ***Andreas Fuhrer,*** IBM Research - Zurich, Switzerland **INVITED**

Since the invention of the first bipolar transistor, integrated circuits have evolved to incredibly complex, ultra-scaled devices with on the order of 10^9 transistors per chip. Even if these devices no longer rely on bipolar technology, excellent control of highly doped regions is still a critical factor for device performance. Moreover, single dopant atoms in a silicon crystal or nanoscale silicon transistors are thought to be candidates for spin qubits with a long spin lifetime.

The hydrogen resist lithography technique is capable of preparing atomic scale planar dopant devices. This is enabled by a large difference in chemical reactivity of the bare and hydrogen passivated Si (001): 2x1 surface. Using a scanning tunneling microscope (STM), the hydrogen layer of the H:Si (001) surface is locally desorbed with nanometer precision, exposing areas of reactive Si. When a gaseous dopant precursor such as phosphine or diborane is introduced, the hydrogen layer acts as a resist and the dopants stick only to the desorbed areas. Compared to conventional fabrication methods, hydrogen resist lithography enables degenerate d-doping with sub-nanometer lateral resolution and abrupt doping profiles.

We have extended the hydrogen-resist technique to p-type doping with diborane and present electrical transport measurements on p-type dopant wires and a simple planar pn-junction fabricated by STM patterning.

In addition, we have developed a CMOS compatible device platform for STM-based atomic-scale device fabrication. The scheme uses pre-fabricated samples with electrical contacts and alignment markers and a hydrogen terminated, reconstructed Si:H(001) surface that is protected from the ambient environment by a capping chip.

The sample surface can be used directly for STM-patterning and atomic device fabrication after in-situ removal of this capping chip. After STM device-fabrication the samples are reintegrated into the CMOS workflow by hydrophobic bonding for wafer scale contacting.

Full functionality of this approach is demonstrated with magnetotransport measurements on degenerately doped STM patterned Si:P nanowires up to room temperature, made possible by the use of silicon on insulator substrates.

MEMS and NEMS Group
Room 202B - Session MN+2D+AN+MP+NS-ThM

Optomechanics and 2D NEMS

Moderator: Max Zenghui Wang, University of Electronic Science and Technology of China

8:00am **MN+2D+AN+MP+NS-ThM1 Towards Microwave to Telecom Wavelength Quantum Information Transfer using Cavity Optomechanics**, ***John Davis,*** University of Alberta, Canada **INVITED**

The past few years have seen the rapid maturation of quantum information processors, particularly in the category of superconducting microwave circuits. With claims from leading companies that they will commercialize quantum processors in the next five years, we must wonder what quantum technologies should be developed in tandem to fully utilize these processors. For example, we are all acutely aware that while our personal computers are powerful, they are considerably more useful and interesting when networked together. So how can we likewise network quantum processors? Especially since the microwave signals of superconducting processors cannot be transmitted at room temperature without thermal decoherence. What if instead, one could link superconducting processors together through existing fiber-optic networks, which are already capable of long distance quantum information transfer? Hence the development of a transducer of quantum information from the microwave to telecom domain has become highly desirable. I will describe the current state of microwave to optical transducers, and how our lab is working towards this goal. Specifically, I will discuss the progress and challenges associated with the development of fiber-coupled telecom-wavelength cavity optomechanical resonators, and 3D superconducting microwave cavities, operating at millikelvin temperatures. I will also discuss ongoing collaborations that could enable implementation of quantum information transducers in a large-scale fiber network in Alberta.

11:20am **MN+2D+AN+MP+NS-ThM11 Reconfigurable Resonant Responses in Atomic Layer 2D Nanoelectromechanical Systems (NEMS)**, ***Zenghui Wang,*** University of Electronic Science and Technology of China*; R. Yang, P.X.-L. Feng,* Case Western Reserve University

Atomic layer semiconducting crystals have emerged as a new class of two-dimensional (2D) materials, exhibiting great promises for both fundamental research and technological applications. Their outstanding electromechanical properties make these materials ideal for constructing novel 2D NEMS, providing opportunities for leveraging their unique device properties across multiple information-transduction domains, at scales down to individual atomic layers. One particularly interesting category of 2D NEMS is 2D nanoelectromechanical resonators, which hold potentials for making the next generation RF signal transduction and processing components, with miniaturized size, ultra-low power consumption, and compatibility with transparent and flexible circuits.

Towards future applications in the 5G era, multi-band RF signal handling capability is desired, as the number of bands each mobile device need to have access to significantly increases, and it would be impractical to simply increase the number of RF components that can only function under one RF frequency, as the space required for mounting such components scales with the number of bands. Therefore, ultralow-power tunable and reconfigurable RF devices that can adapt to different frequencies would be one solution to this challenge.

Here we present experimental demonstration of nanomechanical resonators based on layered MoS_2 atomic crystals that have reconfigurable resonant responses. By carefully studying the temperature-dependent frequency response in such MoS_2 resonators[1], we discover clear, repeatable hysteretic behavior as the device temperature is changed[2]. Leveraging this phenomenon, we achieve switchable resonance frequency f_{res} in such devices by using heating and cooling pulses. Specifically, for an example MoS_2 resonator, during heating pulses, the f_{res} decreases to ~20MHz. Once the device recovers to room temperature, f_{res} stabilizes at ~26MHz. During cooling pulses, f_{res} increases to ~29MHz, and upon reverting to room temperature f_{res} stays at ~24.5MHz, which is clearly different than the other room temperature state. Our findings suggest that such atomic-layer MoS_2 NEMS resonators could be used towards developing reconfigurable RF components whose frequency response can be switched between different states.

[1] R. Yang, et al., *IEEE UFFC, pp 198-201,* 2015. [2] Z. Wang, et al., *IEEE UFFC*, *pp* 783-786, 2015.

11:40am **MN+2D+AN+MP+NS-ThM12 Cavity Optomechanics: Dynamics and Applications**, ***Eyal Buks,*** Israel Institute of Technology, Israel **INVITED**

The field of cavity optomechanics deals with a family of systems, each composed of two coupled elements. The first one is a mechanical resonator, commonly having a low damping rate, and the second one is an electromagnetic cavity, which typically is externally driven. Both radiation pressure and bolometric force can give rise to the coupling between the mechanical resonator and the cavity. In recent years a variety of cavity optomechanical systems have been constructed and studied, and phenomena such as mode cooling, self-excited oscillation, and optically induced transparency have been investigated. The first part of the talk will be devoted to some dynamical effects including synchronization and intermittency. In the second part some applications of optomechanical cavities for sensitive sensing will be discussed.

Nanometer-scale Science and Technology Division
Room 102B - Session NS+AN+EM+MI+MN+MP+PS+RM-ThM

Nanopatterning and Nanofabrication

Moderators: Brian Hoskins, National Institute of Standards and Technology (NIST), Meredith Metzler, University of Pennsylvania, Leonidas Ocola, IBM Research Division, T.J. Watson Research Center

8:00am **NS+AN+EM+MI+MN+MP+PS+RM-ThM1 Femtosecond Laser Processing of Ceria-Based Micro Actuators**, *J. Shklovsky,* Tel Aviv University, Israel*; E. Mishuk,* Weizmann Institute of Science, Israel*; Y. Berg,* Orbotech Ltd, Israel*; N. Vengerovsky, Y. Sverdlov,* Tel Aviv University, Israel*; I. Lubomirsky,* Weizmann Institute of Science, Israel*; Z. Kotler,* Orbotech Ltd*; S. Krylov, Y. Shacham-Diamand,* ***Erez Benjamin,*** Tel Aviv University, Israel

The integration of piezoelectric and electrostrictive materials into micromachined Si devices is viewed as an important technological milestone for further development of Microelectromechanical Systems (MEMS). Recently, it was demonstrated that gadolinium-doped ceria (CGO) exhibits very large electrostriction effect, which results in large electrostrictive strains and high energy densities under very low frequencies (0.01 – 1 Hz). Lead-free CGO is chemically inert with respect to Si, making it an attractive candidate for implementation in MEMS actuators. However, the integration of CGO into MEMS devices is challenging due problems associated with using conventional patterning techniques involving lithography and etching.

In this work, we have successfully created functional double-clamped beam micro-actuators made of CGO films confined between the top and bottom Al/Ti electrodes. The stack containing the electrodes and the ≈ 2 µm-thick CGO film was first blanket-deposited on top of the Si wafer. Cavities were then deep reactive ion etched (DRIE) in the wafer leading to forming of the free-standing rectangular membranes, 1.5 mm × 0.5 mm in size. Finally, ≈ 1.2 mm long and ≈ 100 µm wide the double-clamped beams were cut from the membranes using a femtosecond (fs) laser, demonstrating an unharmful technique for CGO patterning. Laser pulse energies, overlaps and number of line passes were varied during the experiments, to achieve successful cuts through the suspended layer by a clean ablation process. The optimized process conditions were found at a fluence of ~0.3 J/cm^2 for a pulse width of 270 fs, where minimal damage and accurate processing was achieved with minimized heat-affected zones.

Resistivity measurements between the top and the bottom electrodes before and after fs laser cutting revealed that the cutting has no influence on the electric parameters of the device and no electrical shorts are introduced by the laser processing. Vertical displacement measurements under bipolar AC voltage (up to 10 V), at the frequency range of 0.03 – 2 Hz, demonstrated the functionality of the micro-actuator. A displacement of ≈ 45 nm at the voltage of 10 V at 50 mHz was achieved. The actuator didn't show any mechanical or electrical degradation after continuous operation. Our data confirm that fs laser cutting is a useful technique for processing CGO films. The developed techniques may be expanded to other materials used for fabrication of MEMS devices, enabling fast, high yield and high-quality patterning of materials that are challenging to pattern using conventional etching-based methods.

*Three first authors contributed equally to this abstract.

8:20am **NS+AN+EM+MI+MN+MP+PS+RM-ThM2 Synthesis of Functional Particles by Condensation and Polymerization of Monomer Droplets in Silicone Oils**, ***Prathamesh Karandikar***, *M. Gupta,* University of Southern California

The initiated chemical vapor deposition (iCVD) process is an all-dry, vacuum process used to deposit a wide variety of functional polymers. Typically, the monomer and initiator radicals are introduced simultaneously at process conditions leading to undersaturation of monomer vapors. In this work we report a sequential vapor phase polymerization method in which monomer droplets were first condensed onto a layer of silicone oil and subsequently polymerized via a free radical mechanism to fabricate polymer particles. The viscosity of the silicone oil was systematically varied from 100 cSt through 100,000 cSt. A heterogeneous particle size distribution was produced at low viscosities of silicone oil where the smaller particles were formed by the cloaking and engulfment of monomer droplets nucleated at the vapor-liquid interface and the larger particles were formed by coalescence inside the liquid. Coalescence could be inhibited by increasing the viscosity of the silicone oil leading to a decreased average radius and a narrower size distribution of the polymer particles. A transition to polymer film formation was observed for the 100,000 cSt silicone oil substrates. We studied the polymerization of two different monomers, 4-vinyl pyridine and 2-hydroxyethyl methacrylate, since these polymers have a variety of useful properties such as pH-responsiveness and biocompatibility. Our process enables fabrication of functional particles with average diameters ranging from 100 nm – 500 nm with fast reaction times (≈ 15 min). The advantages of our method for the fabrication of polymer particles are that it does not require surfactants or organic solvents and features short reaction times compared to conventional polymer particle synthesis methods such as emulsion polymerization.

8:40am **NS+AN+EM+MI+MN+MP+PS+RM-ThM3 Competition Between Scale and Perfection in Self-assembling Structures**, ***James Liddle***, NIST Center for Nanoscale Science and Technology **INVITED**

Biology relies on self-assembly to form complex, highly-functional structures, inspiring the search for synthetic systems capable of forming similarly complex structures. Such systems typically operate under diffusion-limited, near-equilibrium conditions, making the problem even more challenging. Multi-functional, molecularly-addressable nanostructures of arbitrary shape can be built using DNA-mediated self-assembly. While this is a powerful method, and recent developments in DNA nanostructure fabrication have expanded the available design space, fabrication based on DNA alone can suffer from low yields and is hampered by the need to trade off size and mechanical rigidity.[1,2]

We have been working to both understand the factors that limit the yield of self-assembled structures, and to devise approaches to overcome them. As the number of discrete components used to assemble a structure increases, yield decreases exponentially. We circumvent this limit, by using a two-stage, hierarchical self-assembly process, which allows us to create large structures with high yield.[3] Our process employs a small number of discrete, sequence-specific elements to shape the structure at the nanoscale and define the large-scale geometry. A generic building block – a DNA binding protein, *RecA* – rigidifies the structure without requiring any unnecessary information to be added to the system.

Blending sequence-specific and structure-specific elements enables us to expand the self-assembly toolbox and make micrometer-scale, rigid, molecularly-addressable structures. More generally, our results indicate that the scale of finite-size self-assembling systems can be increased by minimizing the number of unique components and instead relying on generic components to construct a framework that supports the functional units.

[1] Murugan, A., Zou, J. & Brenner, M. P. Undesired usage and the robust self-assembly of heterogeneous structures. *Nat. Commun.* **6**, 6203, doi:10.1038/ncomms7203 (2015).

[2] Schiffels, D., Liedl, T. & Fygenson, D. K. Nanoscale structure and microscale stiffness of DNA nanotubes. *ACS Nano* **7**, 6700-6710, doi:10.1021/nn401362p (2013).

[3] Schiffels, D, Szalai, V. A., Liddle, J. A., Molecular Precision at Micrometer Length Scales: Hierarchical Assembly of DNA–Protein Nanostructures, *ACS Nano*, **11**, 6623, (2017)

9:20am **NS+AN+EM+MI+MN+MP+PS+RM-ThM5 Polymer Templated Annealing of DNA Patterned Gold Nanowires**, ***Tyler Westover***, *B. Aryal, R.C. Davis, A. Woolley, J. Harb,* Brigham Young University

Using DNA origami as a bottom up nanofabrication technique, gold nanowires are formed via directed assembly of gold nanorod seeds and connected by electroless plating. This metal deposition process results in wires with low conductivities compared to bulk gold. Junctions between plated seeds are likely the cause of this low conductivity. Annealing of the nanowires could potentially improve the conductance, however, nanowire annealing at low temperatures (200° C) results in wires coalescing into beads. A polymer encapsulation layer was deposited to maintain overall nanowire shape during annealing. The polymer templated anneal resulted in a resistance reduction, in some cases, to below 1000 ohms. Resistance measurements were performed using a four point resistance configuration. Electrical contacts to the randomly oriented 400 nm long wires were made by electron beam induced deposition. Nanowire morphology was measured before and after annealing by scanning electron and high resolution transmission electron microscopy.

11:00am **NS+AN+EM+MI+MN+MP+PS+RM-ThM10 Directed Self-assembly of Block Copolymers for Applications in Nanolithography**, ***Paul Nealey***, University of Chicago **INVITED**

DSA of block copolymer films on chemically nanopatterned surfaces is an emerging technology that is well-positioned for commercialization in nanolithography and nanomanufacturing. DSA of (PS-b-PMMA) films on lithographically defined chemically nanopatterned surfaces is one focus of our activities in which the main research objectives revolve around understanding the fundamental thermodynamics and kinetics that governs assembly, and therefore patterning properties such as 3D structure, perfection, and processing latitude. A second focus is to use the physical and chemical principles that we have elucidated for DSA of PS-b-PMMA towards the development of block copolymer systems capable of self-assembling into the sub 10 nm regime and continuing to meet the stringent constraints of manufacturing. The research is enabled by the recent development of techniques to combine metrology tools (TEM tomography, GISAXS, RSoXS, high-speed APF), theoretically informed course grained models, and evolutionary algorithms to quantitatively determine and predict the independent process and material parameters that result in different 3D structures of assembled domains.

11:40am **NS+AN+EM+MI+MN+MP+PS+RM-ThM12 Three Dimensional Mesoporous Silicon Nanowire Network Fabricated by Metal-Assisted Chemical Etching**, ***Deepak Ganta***, *C. Guzman, R. Villanueva,* TAMIU

Mesoporous nanowires have gained huge attention due to their applications in energy and sensing. The high surface area along with the quantum confinement effect lead to improved performance of the electrochemical devices during energy conversion and storage. 3D structure or nanowire network improves the reaction site surface area even further along all the three dimensions, enhancing both light and heat absorption. There is also a huge demand for inexpensive, non-lithographic methods to fabricate 3D network of nanowires, which are also mesoporous, with better control of both dimensions and porosity, over a large surface area. They can be very useful in some broad range applications such as solar energy conversion, energy storage, water harvesting, environmental control, bio-sensing, and thermoelectrics.

To address the problem, we report a simple and inexpensive method of fabricating 3D mesoporous Si nanowire network by metal-assisted chemical etching (MacEtch). Degenerately doped p-type silicon or p+ silicon wafer (0.001 ~0.005 Ω·cm) was coated with about 22 nm silver film at 350 °C for 5~6 hours in a vacuum furnace (pressure < 3×10 ⁻7 Torr). Scattered silver particles with different sizes were formed as a result of the dewetting process. Then we deposited 10~11 nm of noble metal (Au) at 0.5 Å/s rate, followed by silver lift-off to obtain an Au mesh as an etching mask. The mixture of a chemical solution of HF: H_2O_2: Ethanol = 30:1:1 is used as a chemical etchant under room temperature. The time of immersion of the silicon wafer in the etchant effects the aspect ratio of the silicon nanowire array. After MachEtch, the Au is removed by immersing the sample in the aqua regia solution. The ratio of the chemicals in the etchant will affect the

pore size. The aspect ratio of the silicon nanowire network can be controlled by the etching rate. The etching rate was roughly one µm/min. The 3D network is formed as the length of the 1D silicon nanowires (50 nm -100 nm) was varied, followed by critical point drying to carefully control the uniformity of 3D silicon nanowire network on the entire surface area of the 6-inch silicon wafer.

Analysis of the 3D mesoporous silicon nanowire network was conducted using Scanning Electron microscopy (SEM), and the top view image confirmed the 3D network of silicon nanowires. The pore sizing (2-50 nm) along with the crystallinity confirmed from the high-resolution transmission electron microscopy (TEM) images with the diffraction patterns.

12:00pm **NS+AN+EM+MI+MN+MP+PS+RM-ThM13 Enhancing Light Extraction from Free-standing InGaN/GaN light Emitters Using Bio-inspired Backside Surface Structuring**, *L. Chan, C.D. Pynn, S.P. DenBaars,* ***Michael Gordon,*** University of California at Santa Barbara

A simple, scalable, and reproducible nanopatterning method to create close-packed (moth-eye like) patterns of conical nano- and microscale features on InGaN/GaN LED surfaces, and on the backside outcoupling surface of LED devices, is presented. Colloidal lithography via Langmuir-Blodgett dip-coating using silica masks (d = 170–2530 nm) and Cl_2/N_2-based plasma etching produced features with aspect ratios of 3:1 on devices grown on semipolar (20-21) GaN substrates. The resulting InGaN/GaN multi-quantum well (MQW) structures were optically pumped at 266/405 nm, and light extraction enhancement was quantified using angle-resolved photoluminescence (PL). A 4.8-fold overall enhancement in light extraction (9-fold at normal incidence) relative to a flat outcoupling surface was achieved using a feature pitch of 2530 nm. Extraction enhancement occurs due to the graded-index (GRIN) effect and breaking of the TIR condition via increased diffuse scattering and diffractive effects, the importance of which evolves with moth-eye feature size. PL results also demonstrate that colloidal roughening, which has greater geometric tunability and works on any GaN orientation, is equivalent to current, c-plane only photoelectrochemical (PEC) roughening methods. Patterning the outcoupling backside of a semipolar device, rather than the topside, is also a technologically feasible approach to fabricate electrically pumped devices because it avoids issues associated with making large area (topside) p-contacts, etching close to or into the active emitter region (destroying the MQWs), or disrupting guided modes in thin-film LEDs layers on sapphire. Because of its simplicity, range of optical control, and wide substrate compatibility, the colloidal lithography technique is a promising alternative to existing commercial processes and a future pathway for enhanced extraction engineering in free-standing polar, nonpolar, and semipolar III-nitride LEDs.

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Chen, J.: NS+2D+AN+EM+MN+MP+PC+RM-MoM8, 4
Chow, J.M.: MP+AM+EM+NS-MoA10, 6; MP+AM+EM+NS-MoA8, 6; MP+EM+MN+NS-MoM5, 2
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Corcoles, A.: MP+EM+MN+NS-MoM5, 2
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Giles, A.J.: EM+2D+AN+MI+MP+NS-TuA11, 11
Glaser, E.R.: EM+2D+AN+MI+MP+NS-TuA10, 11; EM+2D+AN+MI+MP+NS-TuA11, 11
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Ho,: NS+2D+AN+EM+MN+MP+PC+RM-MoM1, **3**
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