Monday Morning, October 28, 2013

MEMS and NEMS
Room: 102 A - Session MN+AS+SS-MoM

Fabrication and Multi-scale Interactions of Materials, Surfaces, and Interfaces at the Micro- and Nano-scale
Moderator: A.V. Sumant, Argonne National Laboratory

8:20am **MN+AS+SS-MoM1 Enhancing Selectivity and Sensitivity of Microfabricated Sensors using Multi-Scale Interactions**, ***T.G. Thundat***, University of Alberta, Canada **INVITED**

Achieving selectivity and sensitivity simultaneously in microfabricated chemical sensors has been a longstanding challenge. Chemical selectivity based on immobilized chemoselective receptors on sensor surfaces fails to achieve speciation in complex environments due to the generality of molecular interactions. However, by incorporating functions which can provide orthogonal signals, it is possible to achieve selectivity, sensitivity, and fast regeneration in miniature sensors. Modulating the physical properties of the surface adsorbed target molecules provides multi-scale information which can be analyzed for molecular recognition. The physical patterning of the sensor surface increases the number of target molecules adsorbed on the surface which results in higher sensitivity. I will discuss recent advances in the integration of multimodal signal generation onto a single platform in microfabricated sensors in order to achieve selectivity, sensitivity, and fast regeneration.

9:00am **MN+AS+SS-MoM3 Meso Scale MEMS Inertial Switch Fabricated using Electroplated Metal on Insulator (MOI) Technique**, *Y. Gerson, D. Schreiber,* Tel Aviv University, Israel, *H. Gerou,* Microsystems Design Center, RAFAEL LTD, ***S. Krylov***, Tel Aviv University, Israel

Micro switches triggered by inertia are widely used as safety and protection devices in airbags, arming and firing systems. These devices are typically fabricated of silicon and incorporate a movable proof mass suspended on flexure-type springs. When a sufficient acceleration is applied, the mass moves towards the fixed electrode resulting in an electrical path that triggers an electric circuit. Electrodeposited metallic devices offer an attractive alternative to silicon in the fabrication of high aspect ratio devices. Nickel is one of the most common materials used for this purpose. The Young's modulus of nickel is close to that of silicon though its density is nearly four times higher and the electric conductivity is five orders of magnitude higher than of highly doped silicon. Nickel is also exceptionally resistant to wet and dry chemical etching, aggressive chemicals and corrosion.

In this work, we report on a novel approach for the fabrication of high aspect ratio electrodeposited nickel MEMS devices. The two mask process is distinguished by its simplicity and does not require formation of anchors/vias for the attachment of the device to the substrate. In this context, similarity between this process and common silicon on insulator (SOI) fabrication paradigm can be mentioned. KMPR negative photoresist is used as a mold due to its ability to yield high aspect ratio structures (>5:1) with vertical sidewalls as well as the relative ease of removal. The devices are fabricated on a 2" single side polished wafers with 4 μm of thermally grown silicon dioxide (TOX). First, a lift-off metallization is performed to define a patterned Cr/Cu seed layer. At the second stage, a 40 μm thick KMPR 1050 negative photoresist is spun on top of the seed layer followed by electrodeposition of a 35 μm thick nickel layer. Next, the stripping of the KMPR mold is performed by ultrasonication bath of remover PG followed by etching with O_2 plasma to remove the resist leftovers. Finally, the wafer is diced into 3mm × 3mm chips and the devices are released first by dipping in a HF to etch the sacrificial oxide and then by etching the copper and chrome. The HF etch time is tailored in such a way that the anchors remain unreleased whereas the free standing elements are released by undercut. The fabricated devices were mounted in a ceramic enclosure and characterized using a drop tester. The triggering event was captured by registered the steep decrease of the resistance down to less than 10 Ω value and functionality of the device was demonstrated in the experiment. Good agreement between the designed values of the triggering time and the experimental data was observed.

9:20am **MN+AS+SS-MoM4 Fabrication and Characterization of Porous Carbon Nanotube Composite Resonators**, ***S. Noyce***, *R.C. Davis, R.R. Vanfleet, D.D. Allred, B.D. Jensen*, Brigham Young University

Porous resonators have the potential to overcome limitations in the micro-resonator field. For example, such structures with high surface area are potentially capable of higher detection limits than solid resonators when used as sensors, due to a higher mass change in a gas or liquid sensing environment. An important consideration for such resonators is the effect of thermo-elastic dampening. We present a versatile micro-resonator fabrication process in which carbon nanotubes are grown from a patterned catalyst, after which the space between the tubes is filled to various degrees of porosity with carbon through Chemical Vapor Deposition. Structural and mechanical characterization data regarding resonators fabricated with this process are presented.

9:40am **MN+AS+SS-MoM5 Fabrication of 3D Nickel Microstructures by Pulsed Electrodeposition on Carbon Coated Carbon Nanotubes**, ***L. Barrett***, *D. Barton, R.C. Davis, R.R. Vanfleet, D.D. Allred*, Brigham Young University

High aspect ratio metallic microstructures have a variety of potential applications in sensing and actuation. However, fabrication remains a challenge. We have fabricated Ni microstructures with aspect ratios greater than 20:1 by electroplating a pattern of carbon coated carbon nanotubes (CNTs). Patterned CNT forests were grown from ethylene by an atmospheric chemical vapor deposition (CVD) at 750ºC followed by a second ethylene CVD step at 900ºC. The second step coats the CNTs and the substrate with a 10nm carbon layer. This coating locks the CNTs together at the points where they touch each other and adheres the CNT forest to the substrate which prevents the forest from deforming or delaminating in the electroplating bath. This carbon coated CNT structure is approximately 95% void space. The void space was then filled with Ni by pulsed electroplating the carbon coated CNTs in a low stress nickel sulfamate bath with a 3ms on time and a 15ms off time. The off time allows the Ni ions to diffuse into the structure to improve uniformity. We will present on the development of the fabrication process and characterization of the resulting C-Ni composite 3D microstructure.

10:00am **MN+AS+SS-MoM6 Dielectric Properties of Electroactive Polymer P(VDF-TrFE-CFE) for Sensor and Actuator Applications**, ***L. Engel***, *S. Kruk, J. Shklovsky, Y. Shacham-Diamand, S. Krylov*, Tel Aviv University, Israel

The rapidly developing field of polymeric electronic and microelectromechanical (MEMS) devices has attracted much attention in recent years. Applications of polymeric MEMS devices include thin film transistors, waveguides for optical sensors, stretchable electronics as well as electroactive polymers (EAP) and dielectric elastomers actuators (DEAs). Polymeric actuators are distinguished by their very low fabrication cost, are often biocompatible, demonstrate large strain under small forces, and exhibit fast response times with relatively large actuation forces and high efficiency. The present work focuses on the integration of the recently developed relaxor ferroelectric polymer poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene)(P(VDF-TrFE-CFE)) with MEMS/NEMS. The high electrostrictive strains, low hysteresis, and high dielectric constant exhibited by this polymer make it particularly attractive for device fabrication, however, these properties depend strongly on the dielectric nature of the polymer. Because of the coupling between P(VDF-TrFE-CFE)'s mechanical behavior and electrical properties, it is critical to device design that we fully understand its dielectric behavior in a MEMS capacity.

We report on the patterning and electrical characterization of a terpolymer of composition VF_2 : 61.3% /VF_3 : 29.7%/CFE : 9% at the micron scale. Through the use of micro-capacitor test structures, we explored the dielectric constant of the P(VDF-TrFE-CFE) as a function of temperature, frequency, and different processing conditions. The morphology of the semi-crystalline polymer under different microprocessing techniques was examined using AFM and XRD, providing a correlation between the material properties and electrical behavior of the polymer. At ~57, the dielectric constant at room temperature of this terpolymer is an order of magnitude higher than is typical for polymers, making P(VDF-TrFE-CFE) attractive for MEMS and in particular, organic electronic type sensors.

Acknowledgements

This project was supported by Arkema/Piezotech. P(VDF-TrFE-CFE) materials were supplied by Piezotech S.A.S

10:40am **MN+AS+SS-MoM8 Silicon Carbide Micro-/Nanosystems for Sensing and Energy Applications**, ***R. Maboudian***, *C. Carraro*, UC Berkeley **INVITED**

Silicon has been the dominant semiconducting material in micro-/nanosystems technologies. However, the material and surface properties of silicon impose limitations on its use in applications involving harsh environment (such as high temperature, high radiation and corrosive conditions). Silicon carbide (SiC), a wide bandgap semiconductor, is emerging as a material to address the limitations of Si as it is temperature tolerant, radiation resistant, and chemically inert. In this talk, I will present recent advances, by our group and others, in the materials science and manufacturing technology of SiC thin film and low dimensional structures. This includes deposition, metallization, and fabrication of semiconductor microdevices, with particular emphasis on sensor and energy technologies.

11:20am **MN+AS+SS-MoM10 Development of Through-Silicon via Contacts for Front Side Electrodes in ISFET Sensors**, *A. Erten*, ***S. Park***, *E. Briggs, D. Martin, Y. Takeshita, T. Martz, A.C. Kummel*, University of California San Diego

Ion-Sensitive Field Effective Transistors (ISFETs) are used for measuring the activity and concentration of ions in solutions. ISFETs are modified Metal-Oxide-Semiconductor FET (MOSFET), which utilize changes in the floating potential on the gate insulator to modulate the current between source and drain. When employed as a pH sensor, ISFETs are operated at constant source-drain current by modulating the potential of the solution via a reference electrode of ISFET. The overall potential change at gate is a direct measurement of the solution pH. Adding an additional gold electrode near the gate region of the ISFET allows the total alkalinity to be determined, which has critical applications in oceanography to study ocean acidification as well as temporary variability in the marine CO_2 system. The gold electrode is used to generate protons (H+) which react with the OH-(aq) thereby neutralizing the pH, which is being monitored by the ISFET gate. This has been successfully demonstrated by using a front side contact to the gold electrode. In a simple 0.5 M NaCl solution, the differences in total alkalinity with 1 milimolar precision were measured within 15 second as predicted by simple device models. However, for practical applications, a backside contact to the front side gold electrode is needed so that all the circuitry and wire bonds can be protected from the solution. In this study, a method for fabrication of through-silicon via contacts for front side electrodes in ISFET dies is discussed. To form backside contacts for front side gold electrodes, it requires patterning and deep etching of a chip with an extremely corrugated topology. The ISFET dies already have two backside quasi-through chip vias for backside contact to the source and drain regions, and this non-planar surface obviates the ability of conventional photoresist coating methods to form a uniform film. A new patterning technique was developed for through-chip etching on highly non-planar surfaces using a roll-on photoresist film to overcome the challenges presented by non-planar surfaces. An oxygen plasma was employed to clean the surface and enhance the adhesion between substrate and photoresist film. In comparison with spray coating and spin coating techniques, roll-on photoresist film method showed significantly improved uniformity and adhesion. This method was also employed to protect the substrate from etch plasma. Reactive ion etching was used to etch away oxide layer before gold deposition and Bosch process. Using through-silicon Bosch etching, a via could be made and gold coating could be employed to contact the front side electrode of ISFET.

11:40am **MN+AS+SS-MoM11 A New MEMS-Based Voltage Controlled Variable Capacitor for Gamma Ray Detection**, ***M. Serry***, *A. Sharaf*, The American University in Cairo, Egypt

This paper reports on a new MEMS-based technique for the rapid and highly sensitive detection of gamma irradiation. The proposed sensor detects small doses of gamma photons through changes in the mechanical and electrical properties of the MEMS structure, which consists of a voltage controlled variable capacitor coated with a gamma photons sensitive polymer. Upon exposure to photons, the polymer crystallizes, triggering a coupled effect: increased stiffness in the folded beam suspensions and altered permittivity, which result in measurable shifts in resonance frequency and capacitance. Based on these mutually reinforcing effects, the proposed design is an unprecedented method for multiplying a sensor's sensitivities for more accurate detection of gamma photons. Two preliminary devices have been fabricated and exposed to gamma radiation doses (5-35 kG) using a Co60 source; the results indicate the sensor's elevated sensitivity (1.1 pf/G), which is higher than current state-of-the-art devices. MEMS integrated devices could replace most current conventional radiation sensors, the majority of which rely mainly on one mode of detection alone—lattice defects in single crystal silicon structures that are induced by irradiation. These defects are detected through resistance or capacitance changes. The current techniques, however, have substantial drawbacks: 1) limited sensitivity; 2) high probability of error; and 3) limited efficacy (i.e., one-time usage). To overcome these drawbacks, we introduce selective electro-deposition of gamma photon sensitive polymers on the combs and folded beam suspensions of the sensors. The mechanical design of the structure yields a more responsive sensor with a stronger output signal by coupling changes in mechanical resonance due to increased stiffness with changes in capacitance as a result of alterations in the dielectric constant of the media. Both effects work together to enhance sensitivity as well as increase the accuracy of the measurements. An SOI wafer is etched on to the front and back sides of the sensor to release the shuttle mass and expose the areas that need to be selectively coated by the gamma-sensitive polymer. Preliminary structures have been employed to test the device's response under different gamma-ray dosages using a Co60 source ranging from 5-35 kG. Capacitance voltage characteristics and the loss factor through the dielectric layer versus the applied voltage across the dielectric media have been characterized. A sensitivity of up to 1.1 pF/G can be achieved.

MEMS and NEMS
Room: 102 A - Session MN+NS-MoA

Optomechanics, Photonics, and Quantum Nanosystems
Moderator: S.L. Burkett, The University of Alabama

2:00pm **MN+NS-MoA1 Silicon Integrated Optoelectronics**, *M. Hochberg, **W. Baehr-Jones***, University of Delaware **INVITED**

CMOS-compatible silicon is not an obvious material system for building high-performance optical devices. But, over the last ten years, it has become possible to build fairly complex integrated optical systems at telecommunications wavelengths on electronics-compatible silicon substrates. In fact the complexity of these systems has been approximately doubling every year, and this trend is projected to continue for at least the next several years. With a combination of CMOS electronics and photonics, we can gain control of both photons and electrons, while preserving the powerful economics of the VLSI revolution. The focus of this talk will be on the OPSIS project, which is a new initiative led out of UW aimed at creating an open infrastructure for building fully integrated optoelectronic devices in silicon, and on some of the new science and engineering that are enabled by these devices.

2:40pm **MN+NS-MoA3 Multiplexed Nanomechanical Devices with Single Wavelength Nanophotonic Actuation and Detection**, ***V.T.K. Sauer**, Z. Diao, M.R. Freeman, W.K. Hiebert*, University of Alberta and The National Institute for Nanotechnology, Canada

Nano-optomechanical system (NOMS) devices offer great opportunity for use in on-chip inertial based mass sensing. They have demonstrated large displacement sensitivity, and their large operational bandwidth allows for very high frequency measurements. These properties are conducive to the transduction of very small nanomechanical resonator motion, and smaller nanomechanical resonators allow for smaller detectable masses. The ultimate goal is to create on-chip sensors that are as sensitive as time-of-flight mass spectrometers. Integrated NOMS systems see a nanomechanical structure modulate the optical properties of a nanophotonic device. This is detected with very high sensitivity by a single probe beam travelling along an integrated nanophotonic waveguide. Optical systems are advantageous in detecting multiplexed arrays of devices due to the reduced complexity of integration. Unlike electrical devices, multiple devices can be probed using a single input and output. This is done by designing the devices to respond to different wavelengths through isolated optical cavities. As a result, multiple signals can be sent along the same waveguide at different wavelength channels to reduce the overall complexity of the design. Here, a multiplexed system is investigated where cantilever and doubly clamped beam nanomechanical resonators are detected using racetrack resonator optical cavities. These devices can also be optically pumped using a modulated laser power in the waveguide which modulates the optical gradient force present on the nanomechanical beam. This is usually done at a wavelength different to the probe laser so the pump signal can be filtered prior to the photo detector. This dual laser pump/probe system can be simplified further using a single beam to act simultaneously as both the pump and probe. Here, the probe laser itself is modulated in power to pump the mechanical motion of the beam. This acts as a homodyne system where the modulated probe power is mixed with the signal created by the nanomechanical beam’s motion. This would further simplify implementation of a multiplexed nanomechanical resonator system due reducing the number of input signals. This homodyne signal is implemented in a phase locked loop using a lock-in amplifier, and the frequency stability is tracked to estimate the mass sensitivity of a single beam driven and detected device.

3:00pm **MN+NS-MoA4 Photonic Readout of Higher Flexural Modes of Nanomechanical Doubly Clamped Beams**, ***Z. Diao**, V.T.K. Sauer, J.E. Losby,* National Institute for Nanotechnology and University of Alberta, Canada*, M.R. Freeman,* University of Alberta and The National Institute for Nanotechnology, Canada*, W.K. Hiebert*, National Institute for Nanotechnology and University of Alberta, Canada

In the past few years nanophotonic transduction, in which a nanomechanical resonator is coupled to a high finesse optical cavity and its displacement is monitored through the cavity near-field has been demonstrated as a highly flexible, ultra-sensitive, wide bandwidth scheme for nanomechanical resonator displacement readout. A common design of the so-called nano-optomechanical devices (NOMS) involves either releasing a part of a nanophotonic waveguide in a race-track optical cavity, so the evanescent field of the guided mode is coupling to the remaining substrate [1], or laterally coupling a doubly clamped mechanical beam to an optical cavity [2]. In both cases, only the fundamental flexural mode is usually investigated [3].

The quest for large bandwidth mass sensors draws attention to higher flexural modes of nanomechanical resonators. Compared to the fundamental flexural mode, higher modes of a mechanical beam offer much higher operating bandwidth while incurring only a modest (or no) increase in its effective mass, depending on the boundary conditions. Higher modes of nanomechanical devices are also of interest for realizing cavity-optomechanics in the resolved-sideband limit [4], and nonlinear modal coupling among different mechanical modes has recently attracted renewed attention [5]. Hence, there is a demand to fully understand the behaviour of higher flexural modes in NOMS devices.

In this work, we fabricate NOMS devices by releasing parts of a nanophotonic waveguide in a race-track optical cavity. Sensitive photonic transduction allows thermomechanical noise of odd flexural modes (up to 50 MHz limited by our measurement electronics) to be observed. However, the transduction responsivity diminishes for even modes, due to the geometrical symmetry of the device design. We show that breaking this symmetry can increase the transduction responsivity for even flexural modes. The nanophotonically transduced displacement responsivity for different modes is also compared to that measured using a free-space interferometry setup. We further discuss the internal stress of the devices and its influence on the mode frequency, shape and transduction responsivity.

[1] W. H. P. Pernice *et al., Opt. Express* **17,** 12424 (2009).

[2] O. Basarir *et al., Opt. Express* **20,** 4272 (2012).

[3] M. Li *et al., Appl. Phys. Lett.* **97,** 183110 (2010).

[4] G. Anetsberger *et al., Nature Physics* **5,** 909 (2009).

[5] M. H. Matheny *et al., Nano Lett.* **13,** 1622 (2013).

3:40pm **MN+NS-MoA6 Progress in Coupling a Superconducting Qubit to Light**, *A.N. Cleland, **J. Bochmann***, University of California, Santa Barbara **INVITED**

My group at UC Santa Barbara has been developing a chip-based, fully integrated microwave-to-optical frequency up-converter based on a piezoelectrically-actuated optomechanical crystal. The device is designed to use the 1550 nm telecommunications wavelength band, trapping photons of that wavelength in an optomechanics crystal, then modulating the frequency of these photons through interactions with GHz-frequency phonons, the latter generated using the piezoelectric response of the crystal. We hope to use this device to create optical frequency entangled photons, produced using entangled microwave-frequency phonon states, generated by a superconducting qubit. This will enable the transfer of quantum information from a millikelvin cryostat to a fiber optic transmission line, with the potential of coupling hybrid quantum systems. I will report on our progress in developing this novel device.

4:20pm **MN+NS-MoA8 Silicon Carbide (SiC) Optical Interferometry for Ultrasensitive Motion Transduction of High Frequency Mechanical Resonators**, ***Z. Wang**, J. Lee, T. He, P. X.-L. Feng*, Case Western Reserve University

We report on the first experimental demonstration of an ultrasensitive laser optical interferometric technology based on thin-film silicon carbide (SiC) micromechanical and nanomechanical resonant systems, which offer motion transduction with displacement sensitivities down to the sub-10fm/rtHz level, at room temperature.

Position and motion detection with advanced optical techniques have been widely used for studying the static and dynamic motions of various systems, ranging from the classical scanning probe microscopes to the emerging resonant nano/microelectromechanical systems (NEMS/MEMS). In particular, in recent years significant efforts and advances [1,2] have been made in developing laser optical interferometric systems based on various NEMS/MEMS resonators, with constituting materials in Si, SiN, GaAs, AlN, and more recently two-dimensional (2D) crystals such as graphene and MoS_2. These advances have kept enabling very sensitive detection of motions in various NEMS/MEMS resonators, with ever improving displacement sensitivities, from ~nm/rtHz to ~pm/rtHz levels. In many of these systems, there are limitations intrinsic to the device structures and constituting materials. For instance, light absorption and parasitic heating effects can compromise these interferometric systems from achieving better sensitivities.

In this work, we explore new optical interferometric techniques by exploiting some unique properties of SiC thin films, particularly the high transparency and ultralow photon absorption (60 times lower than Si) in the wide visible range, as well as the excellent thermal conductivity. The SiC thin films are prepared by low-pressure chemical vapor deposition (LPCVD) on various substrates, which enables us to develop a novel SiC-on-SiO_2 material platform. The suspended MEMS/NEMS devices fabricated in this thin-film platform all share important features such as smooth surfaces and a uniform interferometric gap. These structural features, combined with SiC's outstanding physical properties, have permitted us to demonstrate unprecedented displacement sensitivities at ~5-10fm/rtHz levels, better than other MEMS/NEMS-based optical interferometric techniques reported to date. We demonstrate such ultrasensitive techniques for motion detections in high frequency SiC microdisk resonators and nanocantilever resonators. In both systems, we have measured the undriven, intrinsic thermomechanical resonances up to high-order modes.

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[1] W. K. Hiebert, et al., *J. Micromech. Microeng.* **20**, 115038 (2010).

[2] J. Lee, et al., *Proc. IEEE Inter. Freq. Contr. Symp. (IFCS2012)*, DOI: 10.1109/FCS.2012.6243742.

Graphene and Other 2D Materials Focus Topic
Room: 104 B - Session GR+AS+EM+MI+MN-TuM

Optical, Magnetic, Mechanical and Thermal Properties of 2D Materials
Moderator: A.A. Balandin, University of California, Riverside, D. Gunlycke, Naval Research Laboratory

8:00am **GR+AS+EM+MI+MN-TuM1 Long-range Magnetic Order in a Purely Organic 2D Layer Adsorbed on Epitaxial Graphene**, *M. Garnica, D. Stradi, S. Barja, F. Calleja, C. Diaz, M. Alcami, N. Martin,* ***A.L. Vazquez-de-Parga****, F. Martin, R. Miranda*, Universidad Autónoma de Madrid, Spain

Collective magnetic properties are usually associated to d or f electrons which carry the individual magnetic moments. Band magnetism in organic materials based on π electrons has remained an experimental challenge, in spite of rigorous predictions of a fully spin polarized ground state in half-filled flat band organic systems. Cryogenic Scanning Tunneling Microscopy (STM) and Spectroscopy in UHV and accurate Density Functional Theory (DFT) simulations show that isolated TCNQ molecules deposited on a monolayer of graphene epitaxially grown on Ru(0001) acquire charge from the substrate and develop a sizeable magnetic moment, which is revealed by a prominent Kondo resonance. The magnetic moment is preserved upon dimer and monolayer formation. The self-assembled 2D monolayer of magnetic molecules develops spatially extended spin-split electronic bands visualized in the real space by STM, where only the majority band is filled, thus becoming a 2D, purely-organic magnet whose predicted spin alignment in the ground state is visualized by spin-polarized STM at 4.6 K [1]. Since the added charge occupies spatially extended intermolecular bands with well-defined spin character, one might speculate that the TCNQ monolayer could act as a spin filter or 2D spin polarizer, adding magnetic functionalities to graphene by altering the spin polarization of a current flowing in graphene.

[1] M. Garnica et al, Nature Physics http://dx.doi.org/10.1038/NPHYS2610 (2013)

8:20am **GR+AS+EM+MI+MN-TuM2 Graphene Thermal Properties and Applications for Thermal Management of Li-Ion Batteries**, ***P. Goli****, S. Legedza, A.A. Balandin*, University of California, Riverside

Graphene's superior intrinsic thermal conductivity, flat geometry, flexibility and demonstrated capability for integration with other materials make graphene very promising for thermal management applications [1-2]. The thermal conductivity of graphene flakes incorporated within different materials can degrade due to coupling to the adjacent layers and phonon scattering on defects and edges [2]. At the same time, the thermal conductivity of graphene and FLG in different composite materials can remain relatively high compared to conventional thin films [3]. A possibility of using a mixture of graphene and FLG as fillers in thermal interface materials (TIM) has also been demonstrated [4-5]. In this talk we report on a possibility of using graphene as a filler material in phase-change materials (PCMs) for thermal management of Lithium-ion batteries. Lithium-ion batteries are superior to other types of batteries owing to their high-energy storage density. However, their applications are limited due to strong self-heating effects coupled with the adverse effect of temperature on the battery life-time. Prior work on thermal issues in Li-ion battery packs has demonstrated that a passive thermal management system based on PCMs is a promising approach. The PCM thermal management uses the latent heat stored in the material as its phase changes over a small temperature range. However, PCMs typically have low thermal conductivity (below 1 W/mK at room temperature). They store heat from the batteries rather than transfer it outside. For this reason, the usefulness of PCM passive thermal management for the high-power Li-ion batteries is limited. We found that incorporation of graphene to the hydrocarbon-based PCM allows one to increase its thermal conductivity by more than two orders of magnitude while preserving its latent heat storage ability. A combination of the sensible and latent heat storage together with the improved heat conduction outside of the battery pack leads to a significant decrease in the temperature rise inside a typical Li-ion battery pack. The described combined heat storage – heat conduction approach can lead to a transformative change in thermal management of Li-ion and other types of batteries [6].

[1] A.A. Balandin, et al., Nano Lett., 8, 902 (2008); [2] A.A. Balandin, Nature Mat., 10, 569 (2011); [3] Z. Yan, G. Liu, J.M. Khan and A.A. Balandin, Nature Comm., 3, 827 (2012); [4] K.M.F. Shahil and A.A. Balandin, Nano Lett., 12, 861 (2012); [5] V. Goyal and A.A. Balandin, Appl. Phys. Lett., 100, 073113 (2012); [6] For details, see at http://ndl.ee.ucr.edu [http://ndl.ee.ucr.edu/]

8:40am **GR+AS+EM+MI+MN-TuM3 Graphene Nano-Photonics and Carrier Dynamics**, *F. Koppens,* ***P.A. Gonzalez***, ICFO - The Institute of Photonic Sciences, Spain **INVITED**

In this talk I will review the new and strongly emerging field of graphene nano-photonics. In particular, I will show how to exploit graphene as a host for guiding, switching and manipulating light and electrons at the nanoscale [1,2]. This is achieved by exploiting surface plasmons: surface waves coupled to the charge carrier excitations of the conducting sheet. Due to the unique characteristics of graphene, light can be squeezed into extremely small volumes and thus facilitate strongly enhanced light-matter interactions.

One particular example of these enhanced light-matter interactions is the non-radiative energy transfer from light emitters to graphene. We experimentally and theoretically quantified this energy transfer process and find that the emitter decay rate follows a universal distance-scaling relation and is enhanced by a factor 90 [3].Additionally, I will discuss novel types of hybrid graphene photodetectors [4] and new excitating results on carrier dynamics and carrier multiplication in graphene. By studying the ultrafast energy relaxation of photo-excited carriers after excitation with light of varying photon energy, we find that electron-electron scattering (and thus carrier multiplication) dominates the energy relaxation cascade rather than electron-phonon interaction [5]. This singles out graphene as a promising material for highly efficient broadband extraction of light energy into electronic degrees of freedom, enabling a new class of high-efficiency optoelectronic and photovoltaic applications.

References

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[2] F. Koppens, D. Chang, J. García de Abajo, "Graphene Plasmonics: A Platform for Strong Light–Matter Interactions", Nano Letters 11, 3370–3377 (2011).

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[5] K.J. Tielrooij, J.C.W. Song, S.A. Jensen, A. Centeno, A. Pesquera, A. Zurutuza Elorza, M. Bonn, L.S. Levitov, and F.H.L. Koppens. Nature Physics (2012)

9:20am **GR+AS+EM+MI+MN-TuM5 Graphene Mechanics and NEMS Applications**, ***J.C. Hone***, Columbia University **INVITED**

This talk will review collaborative efforts in characterizing the mechanical properties of graphene, and its application to nano-electromechanical devices (NEMS). We use nano-indentation of freely suspended membranes to measure mechanical properties. These measurements, when combined with nonlinear anisotropic continuum modeling, reveal that graphene is both ultrastiff (in-plane Young's modulus equivalent to 1 TPa) and the strongest known material (in-plane breaking strength equivalent to 100 GPa). Our recent work demonstrates that CVD-grown graphene, even in the presence of grain boundaries, can retain almost all of this intrinsic strength, opening the door to large-area high-strength films. For NEMS applications, we have developed techniques that allow fast, highly sensitive electronic readout. We are applying graphene NEMS to studies of fundamental physics in the quantum Hall regime and applications in electro-mechanical signal processing. In particular, I will dsicuss our recent work on graphene voltage controlled oscillators for generation of frequency modulated signals.

10:40am **GR+AS+EM+MI+MN-TuM9 Nano-plasmonic Phenomena in Graphene**, ***D.N. Basov***, University of California San Diego **INVITED**

Infrared nano-spectroscopy and nano-imaging experiments have uncovered rich optical effects associated with the Dirac plasmons of graphene [*Nano Lett. 11, 4701 (2011)*]. We were able to directly image Dirac plasmons propagating over sub-micron distances [*Nature 487, 82 (2012)*]. We have succeeded in altering both the amplitude and wavelength of these plasmons by gate voltage in common graphene/SiO_2/Si back-gated structures. Scanning plasmon interferometry has allowed us to visualize grain boundaries in CVD graphene. These experiments revealed that grain boundaries tend to form electronic barriers that impede both electrical transport and plasmon propagation. Our results attest to the feasibility of using electronic barriers to realize tunable plasmon reflectors: a precondition for implementation of various metamaterials concepts. Finally, we have carried out pump-probe experiments probing ultra-fast dynamics of plasmons in exfoliated graphene with the nano-scale spatial resolution.

11:20am **GR+AS+EM+MI+MN-TuM11 Controlled Growth of Large-Area Mono-, Bi-, and Few-Layer Graphene by Chemical Vapor Deposition on Copper Substrate**, ***C.-Y. Park****, Y. Kim*, Sungkyunkwan University, Republic of Korea

Direct synthesis of graphene using a chemical vapor deposition (CVD) has been considered a facile way to produce large-area and uniform graphene film, which is an accessible method from an application standpoint. Hence, their fundamental understanding is highly required. Unfortunately, the CVD growth mechanism of graphene on Cu remains elusive and controversial.

Here, we present the effect of graphene growth parameters on the number of graphene layers were systematically studied and growth mechanism on copper substrate was proposed. Parameters that could affect the thickness of graphene growth include the pressure in the system, gas flow rate, growth pressure, growth temperature, and cooling rate. We hypothesis that the partial pressure of both the carbon sources and hydrogen gas in the growth process, which is set by the total pressure and the mole fraction of the feedstock, could be the factor that controls the thickness of the graphene. The graphene on Cu was grown by the diffusion and precipitation mode not by the surface adsorption mode, because similar results were observed in graphene/Ni system. The carbon-diffused Cu layer was also observed after graphene growth under high CH_4 pressure. Our findings may facilitate both the large-area synthesis of well-controlled graphene features and wide range of applications of graphene.

11:40am **GR+AS+EM+MI+MN-TuM12 Charged Vacancy Defects in Graphene: Stability and Charge States**, *Y. Liu, M. Weinert,* ***L. Li***, University of Wisconsin Milwaukee

We perform atomic resolution imaging of vacancy defects in graphene using non-contact atomic force microscopy, and directly determine their charges by local contact potential difference measurement. We observe reconstruction, healing, and merging of vacancy defects. Combined with first-principles calculations, we further show that vacancy defects are typically positively charged, while H adsorbates at these sites can produce negatively charged structures, and their charge states are not necessarily integer-valued. These results provide new insights into the stability of charged vacancy defects in graphene, as well as the functionalization of graphene for chemical sensing and catalysis, and underline the tunability of these functions by controlling the size and doping of vacancy defects.

MEMS and NEMS
Room: 102 A - Session MN+NS-TuM

Micro and Nano Systems based on Carbon and Piezoelectric Materials
Moderator: P. X.-L. Feng, Case Western Reserve University

8:00am **MN+NS-TuM1 Science and Technology of Integrated Piezoelectric and Ultrananocrystalline Diamond Films for a New Generation of High Performance MEMS and NEMS Devices**, ***O. Auciello***, University of Texas at Dallas **INVITED**

This review will focus on a discussion of the science and technology for a novel integration of ultrananocrystalline diamond (UNCD) and piezoelectric thin films to enable a new generation of hybrid piezo/diamond heterostructures for low voltage piezoactuated high-performance diamond-based MEMS/NEMS devices. A main component of the new MEMS/NEMS systems is the new UNCD film discovered, developed and patented by our group. UNCD exhibits multifunctionalities applicable to a broad range of multifunctional devices from the macro to the nanoscale. UNCD films are grown using plasma enhanced chemical vapor deposition (PECVD) with a new patented Ar-rich/CH_4 chemistry, which yields insulating films with 2-5 nm grains and 0.4 nm wide grain boundaries or electrically conductive films (NUNCD), with 10 nm grains and 1-2 nm grain boundaries, via nitrogen incorporation into grain boundaries when growing the film with an Ar/CH_4/N_2 gas mixture.

Concurrently with the development of the UNCD film technology, our group has been developing a ferroelectric/piezoelectric thin film technology, based on three main piezo materials ($PbZr_xTi_{1-x}O_3$, AlN, and the newest $BiFeO_3$), and the UNCD/piezoelectric thin films integration, which are being used to develop new low voltage/high performance piezoactuated MEMS/NEMS devices for several applications, namely: energy harvesting devices, piezoactuated NEMS switches for a new NEMS logic, biosensors, implantable MEMS/NEMS drug deliver devices, and biologically enabled piezo-MEMS micro-power generators.

In addition to the application to piezo-actuated MEMS, UNCD has been demonstrated as a unique dielectric with fast charging-discharging (in the microsecond range) layer that eliminates RF MEMS switch charging-induced failure, due to fast charge motion in and out of the film through the nano-grain boundaries, enabling a new technology based on reliable RF-MEMS switches integrated with driving CMOS devices for a new generation of phase array antennas for radars and mobile communication devices.

8:40am **MN+NS-TuM3 Utilizing Piezoelectric MEMS Across Length Scales**, ***S. Trolier-McKinstry***, Penn State University **INVITED**

Piezoelectric microelectromechanical systems offer an interesting way of achieving sensing and actuating capabilities on-chip, at voltage levels that are compatible with many CMOS devices. As a result, there is a burgeoning interest in exploiting films that can produce large strains over a wide range in length scales. This talk will address the use of perovskite thin films (especially $PbZr_{0.52}Ti_{0.48})O_3$, PZT, and $70PbMg_{1/3}Nb_{2/3}O_3 - 30PbTiO_3$, PMN-PT) in applications where the critical dimensions range from tens of nm to meters. Particular attention will be placed on 1) use of actuators to correct figure errors in next-generation X-ray space telescopes and 2) a potential CMOS – replacement technology for computation which hinges on use of a piezoelectric thin film to drive a resistance change in a piezoresistor.

On the extreme upper end are large area devices for applications such as adaptive optics. In this case, the piezoelectric film can be used to produce local deformation of a mirror surface, in order to correct figure errors associated with fabrication of the component or to correct for atmospheric distortion. For example, should a mission such as Gen-X be flown, it would require up to 10,000 m^2 of actuatable optics in order to correct the figures of the nested hyperboloid reflecting segments. The piezoelectric layers were deposited by sputtering; the best insulation properties were obtained in films that avoided lead excess phases at the grain boundaries. Measurements of the influence function resulting from actuation of one or more of the piezoelectric cells (to change the local curvature of the substrate) demonstrate that such adjustable optics should be able to increase the resolution of X-ray telescopes by an order of magnitude.

A fast, low power, transistor-type switching device has been proposed in which piezoelectric and piezoresistive materials are employed in a stacked sandwich structure of nanometer dimension. Of particular interest to this program is the functionality of the high aspect ratio piezoelectric $70Pb(Mg_{1/3}Nb_{2/3})O_3$-$30PbTiO_3$ (PMN-PT) component. PMN-PT films of 0.3 – 1.1 microns in thickness were made by a 2MOE solvent sol-gel route. These films were phase pure by XRD with dielectric constants exceeding 1500 and loss tangents of approximately 0.05. The films showed slim hysteresis loops with remanent polarizations of about 8 $\mu C/cm^2$ and breakdown field > 1.5 MV/cm. The films exhibited large signal strain > 1% with $d_{33,f}$ of approximately 80 pm/V. It has been found that laterally patterning the piezoelectric layer in this case produces an increased dielectric response indicative of a reduction in substrate-induced clamping.

9:40am **MN+NS-TuM6 Two-Dimensional (2D) MoS_2 Semiconducting Crystal Nanomechanical Resonators with Frequency Scaling**, ***J. Lee****, Z. Wang, K. He, J. Shan, P. X.-L. Feng*, Case Western Reserve University

We report the first demonstration of resonant nanoelectromechanical systems (NEMS) based on ultrathin molybdenum disulfide (MoS_2) crystals down to only a few atomic layers, with measurements of resonances in the high frequency and very high frequency (HF/VHF) bands, and studies of frequency scaling pathways toward the ultrahigh frequency (UHF) and microwave regimes. Atomically-thin two-dimensional (2D) crystals have recently shown interesting promises for enabling new nanoelectronic and optoelectronic devices [1]. The unique mechanical properties of these 2D crystals, including excellent elastic modulus (~0.2-1TPa) and extremely high strain limits (~10^2-10^3 times higher than in 3D crystals), also make them attractive for 2D NEMS [2,3]. To date, most 2D NEMS have been based upon graphene, the hallmark of 2D crystals. 2D MoS_2, an ultrathin crystal of transition metal dichalcogenides (TMDCs), has emerged as a new class of 2D layered materials beyond graphene. Unlike graphene being a semimetal, 2D MoS_2 is a semiconducting crystal with a sizeable bandgap and hence opens up new device opportunities. In this work, we describe experiments on realizing drumhead-structured MoS_2 NEMS resonators based upon suspended MoS_2 diaphragms as thin as 6nm (9 layers of the crystal unit cell). We demonstrate resonators operating at up to ~60MHz in the VHF band at room temperature, with measurements of Brownianmotion thermomechanical noise spectra. We also measure quality (*Q*) factors of these MoS_2 resonators and explore the dominating energy dissipation mechanisms in these 2D structures. The extensive measurements and analysis in this work with many devices establish MoS_2 as a new material for frequency-scalable 2D NEMS resonators and transducers. Our study opens up possibilities for new types of NEMS, where the mechanical properties of 2D MoS_2 can be coupled to its semiconducting attributes.

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[1] Q. H. Wang, *et al.*, *Nature Nanotechnology* **7**, 699-712 (2012).

[2] R. A. Barton, *et al.*, *J. Vac. Sci. Technol. B* **29**, 050801 (2011).

[3] J. Lee, P. X.-L. Feng, *Proc. IEEE Inter. Freq. Contr. Symp. (IFCS2012)*, DOI: 10.1109/FCS.2012.6243742

MEMS and NEMS
Room: Hall B - Session MN-TuP

MEMS and NEMS Poster Session

MN-TuP1 Analysis of Convective Performance in Confined Droplets with Various Working Fluids and Substrates for Polymerase Chain Reaction Applications, *P.L. Chen, C.S. Yu, C.C. Yang, Y.H. Lin, Y.H. Tang, M.H. Shiao, C.-N. Hsiao*, National Applied Research Laboratories, Taiwan, Republic of China

Polymerase chain reaction (PCR) is a procedure which repeating thermal cycles with three discrete temperature steps, including denaturation (95°C), annealing (60 °C), and extension (72 °C) for deoxyribonucleic acid (DNA) amplification. It usually takes 1 or 2 hour to complete the PCR process in commercial equipment. In order to reduce reagent solution and increase heat transfer rate, micro-electro-mechanical-systems (MEMS) and microfluidic technologies are utilized to miniaturize the PCR system. Furthermore, a new concept for the development of microchips that uses Rayleigh-Bénard (RB) convection to perform PCR amplification of DNA is rapidly increased in the past few years. However, the challenges for RB-PCR devices involve the control of flowing performance and chemical pollution . The aim of present work is to investigate the convective performance in a 2 µl droplet for the application of real-time PCR with computational fluid dynamics (CFD) techniques. The influence of several major parameters, such as the viscosity and density of working fluid, and the type of substrate on the overall temperature distribution, pressure drop and velocity distribution were all analyzed and discussed. The simulated results show that the steady state was reached in 3 seconds and 30 cycles were completed in 10 minutes inside the droplet by controllable flowing conditions. The droplet based RB-PCR device offers a miniaturized thermal circulation system by natural convention without tedious three steps temperature control or flow control and potentially applicable for real-time DNA microarray analysis.

MN-TuP2 The Study of Convex Corner Compensation for Dry Anisotropic Etching of Single Crystal Silicon in ICP-RIE, *Y.H. Lin, Y.H. Tang,* ITRC, NARL, Taiwan, Republic of China, *W. Hsu,* NCTU, Taiwan, Republic of China, *P.-L. Chen, C.C. Yang, M.-H. Shiao, C.-N. Hsiao*, ITRC, NARL, Taiwan, Republic of China

In this paper, the compensation structure assisted the convex corner structures etch in inductively coupled plasma reactive ion etch (ICP-RIE) have been studied. The convex corner structures are widely used in many applications like micro optical devices or micro sensors. There are many researches to discuss the convex corner structure under wet etch, but rare researches for dry ICP-RIE etching. In anisotropic silicon etching, under the Bosch patent, sequentially alternating etch and passivation cycles can easily achieve high aspect ratio silicon structures. The feature size of the convex corner structures is difficult to maintain as original design at the bottom position in deep etch, due to some non-vertical movement plasma. The non-vertical movement plasma caused by collision between plasma ions, pollutants or rebounded from the etching mask. The compensation structure is design in front of the convex corner structure. The compensation structures can obstruct the non-vertical plasma to etch the convex corner structure and reduce the etch lag effect during the etch process leading to better profile at deep etch. The current study systematically investigates plasma condition to verify feasibility of the proposed method, and discusses effect of the gap between compensation structure and convex corner structure at three different gaps of 15, 10, 5µm. It demonstrate the convex corner structure have better profile with compensation structure at 5µm gap than other at deep ICP-RIE etching.

***Keywords*:** Convex corner compensation, Inductively-Coupled-Plasma Reactive-Ion-Etch (ICP-RIE), High-aspect-ratio structure

MN-TuP3 Micro Fabrication on Quartz Glass by Inductively Coupled Plasma-reactive Ion Etching and its Optical Application, *Y.H. Tang, Y.H. Lin, P.-L. Chen, M.-H. Shiao, C.-N. Hsiao*, ITRC, NARL, Taiwan, Republic of China

The etching characteristics of inductively coupled plasma-reactive ion etching (ICP-IRE) on the micro structure of quartz glass were investigated with a negative photoresist (KMPR 1050) etching mask material. We found that a nearly vertical side wall of the fabricated quartz glass profile with KMPR 1050 mask (negative photoresist). Detailed process characterization was performed by varying the process parameters which include ICP power, bias power and chamber pressure. In the case of KMPR mask, which has excellent material strength and good verticality, the etched micro structure exhibited a depth of 44.6 µm and vertical sidewall angle of 89° by means of ICP power 1500 W, bias power 120 W, and chamber pressure at 10 mTorr under a mixture gas of C_4F_8 and He at 12 and 84 sccm of flow rates, respectively. Moreover, the etching rate was controlled approximately at 0.249 µm per minute, the etching selectivity was more than a ratio of 1:2, and the roughness of etched surface was around 12.9 nm. Furthermore, the advantage of pattern transfer with high resolution and high accuracy has been demonstrated by fabricating subwavelength structure (SWS), achieving broadband antireflection (AR) and increasing the transmittance of incident light across the quartz glass. Consequently, smoothly tapered SWS surfaces with a width of 105 nm and a height of 190 nm could be produced on quartz wafer. This fabricated SWS decreased the surface reflectance to less than 6.75 % in the visible light spectrum.

MN-TuP4 Finite Element Model Verification of High Frequency Piezoelectric Contour-Mode MEMS Resonators Using Laser Vibrometry, *K.R. Qalandar, B.A. Gibson, L.A. Shaw, S.Y. Chiu,* University of California, Santa Barbara, *A. Tazzoli, J. Segovia,* Carnegie Mellon University, *M. Rinaldi,* Northeastern University, *G. Piazza,* Carnegie Mellon University, *K.L. Turner*, University of California, Santa Barbara

This paper reports the first FEA model verification of AlN contour-mode resonators (CMRs) using laser Doppler vibrometry (LDV) at frequencies above 1GHz. Full 3D models of UHF resonators are able to determine electrical and mechanical responses, including AF response, admittance curves, and full 3D mode shapes. The modal analysis here differs from previous works [1-3] by making direct quantitative comparisons between measured and simulated responses.

The 1GHz lateral-field CMRs consist of a thin film of AlN patterned with interdigitated metal electrodes on top and a floating electrode on bottom. An AC signal to the electrodes excites the contour-extensional mode through the equivalent d31 piezoelectric coefficient of the AlN [4,5]. The devices are characterized by mechanical and electrical measurements. A Polytec UHF120 LDV captures phase and out-of-plane displacement data, with ±1.4pm resolution down to a noise floor of 4pm (Fig. 1). Spatial scans across the surface generate 3D mode shapes (Fig. 2). By performing frequency sweeps and fitting data to the equations of motion, we extract mechanical parameters such as the linear and nonlinear stiffness and damping coefficients. Electrical measurements further validate simulation results; through the electromechanical coupling coefficient the mechanical measurements can also be confirmed.

The 3D FEA models are developed in COMSOL and used to determine both mechanical and electrical responses. We compare simulated frequency response, out-of-plane displacement, and Q with experimental data to verify the models (Table 1). Fig. 2 shows the 3D mode shape, and the out-of-plane displacement profile of individual fingers is shown in Fig. 3. The maximum seen in experiments is 119.5pm, which agrees well with the simulated value of 117pm. To compare mechanical response, the wavelength λ in the lateral direction is studied. Simulations show a 3.2um and 7.9um wavelength at resonance. Experimentally, a 4um and an 8um wavelength appear. The multiple wavelengths at resonance are the result of a mismatch in acoustic velocity between AlN and Al and their existence in the simulation serves as further validation. Simplified five-finger device simulations show good fit with experimental admittance (Fig. 4). Full 33-finger device simulations, currently in progress, will improve this fit.

The experimental data gives further insight into the operation of the devices and is essential to the verification the 3D FEA models. With confirmed accuracy, these models can be used for predictive modeling of GHz-range CMRs. This allows optimization of geometric parameters such as electrode spacing and anchor performance.

MN-TuP5 Phase Noise-Based Bifurcation Sensing of Nonlinear MEMS Cantilevers, *L. Li, L.A. Shaw, K.L. Turner*, University of California, Santa Barbara

The objective of this work is to develop a high frequency MEMS-based mass sensor capable of pushing the limits of sensitivity for the detection of explosive materials. The specific objective is to utilize a nonlinear microcantilever mass sensor functionalized with xerogel-based molecularly imprinted polymers (MIPs) for the selective detection of DNT. This paper reports the implementation of a novel control method for sensing which is based on the phase squeezing phenomenon present in the nonlinear dynamics of a parametrically driven microcantilever. It is expected to significantly improve the mass detection limits compared to bifurcation tracking [1], as well as reduce measurement time by over three orders of magnitude. Sensor speed, sensitivity, and selectivity are all important for ppt level DNT/TNT detection.

Previous work focuses on tracking the resonance frequency shift of the microcantilever due to DNT absorption using bifurcation tracking [1]. Bifurcation sensing is achieved by sweeping the frequency or voltage until a jump event occurs, and tracking is done by repeating the process to detect the frequency shift. However, bifurcation tracking is a time-consuming process which requires time to reset the system back to an appropriate initial condition after each jump event to avoid hysteresis before the next bifurcation occurs. This work reports a new method of sensing which concentrates on monitoring changes in the phase response as the device approaches the bifurcation point. Just prior to bifurcation, noise squeezing occurs due to a slowing down of the response component associated with the bifurcating eigenvalue near the bifurcation point. The statistical variance of the phase response serves as a precursor to activate the feedback control scheme, which employs frequency modulation to stabilize a parametrically-excited sensor at the edge of instability. By maintaining close proximity to the bifurcation, but not allowing the large amplitude growth necessary for existing bifurcation tracking methods, over three orders of magnitude measurement time improvements in the acquisition rate near the location of the bifurcation point can be made [2]. Initial results show that the controller is capable of tracking the resonance frequency based on the phase variance of the microcantilever with close proximity to the edge of instability and control parameters can be tuned to optimize the sensitivity of the sensor. DNT gas sensing using the controller is yet to be experimented and the sensitivity of noised squeezing bifurcation sensing of nonlinear MEMS microcantilever is expected to be presented at the conference.

MN-TuP6 Simulation Study of Processing Parameters for Solder Filled Self Assembled 3D Micro-scale Structures, ***N. Oraon***, International Institute of Information Technology, India, *J.C. Lusth, S.L. Burkett,* The University of Alabama, *M. Rao*, International Institute of Information Technology, India

Solder based self assembled (SBSA) structures are formed by transforming 2D patterns to 3D structures. SBSA processing involves conventional lithography, metal deposition, and etching methods in addition to dip soldering and solder reflow. The processing involves free metals around a fixed metal, when reflowed; the free metal pattern is rotated towards the fixed metal pattern till the solder reaches minimum surface energy. In previous work, we investigated two types of soldering: face and edge-soldered SBSA structures. The 3D structure produces an excess solder when the amount of the solder deposited is more than the 3D volume. The excess solder which is measured from the top of the metal structure to the top of the solder in face-soldered SBSA structures is known as solder standoff height (SSH). SSH is envisioned as being useful as a solder bump that could be used to stack hybrid layers in 3D integration schemes. Experimentally, SSH was found to be heat resistant. The simulation study we performed reflects the effect of processing parameters such as gap-size between metal patterns, solder thickness, and solder coverage on the formation of 3D structures. Formation of 3D structures is influenced by the tilt of free metal towards the fixed metal. Hence tilt angle is considered as one of the output parameters. The processing parameters are analyzed for truncated square pyramid (TSP) and open cube (OC) structures using an open source simulation tool, Surface Evolver.

Surface Evolver is an interactive program for the study of surfaces shaped by surface tension. Simulation results show that as the gap size decreases, the minimum solder energy is attained at lower tilt angles for face-soldered TSP and OC structures. Edge-soldered OC structures follow a similar trend. The tilt angle remains constant for a range of gap sizes for edge-soldered TSP structures. Varying solder thickness varies the minimum energy tilt angle for face-soldered structures. For edge-soldered structures, tilt angle remains constant irrespective of solder thickness. Optimum tilt angle remains constant for solder coverage of 70 % and higher in both TSP and OC structures.

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