MEMS and NEMS

Room: 615 - Session MN-TuM

Integration and Packaging in MEMS/NEMS

Moderator: E. Gousev, Qualcomm MEMS Technologies

8:00am **MN-TuM1 Wafer Level Integration of Ultrananocrystalline Diamond (UNCD) Film with CMOS Devices for Monolithically Integrated Diamond MEMS/NEMS-CMOS Systems**, ***A.V. Sumant***, *O. Auciello,* Argonne National Lab, *H.C. Yuan, Z. Ma,* Univ. of Wisconsin-Madison, *B. Kabius,* Argonne National Lab, *V. Adiga, R.W. Carpick,* Univ. of Pennsylvania, *D.C. Mancini*, Argonne National Lab

Most devices for MEMS are currently based on silicon because of the available surface micromachining technology. The average mechanical and tribological properties of Si, however, are not suitable for many high-performance devices for current MEMS and future NEMS, such as resonators and switches which involve mechanical motion and intermittent contact. Other materials, such as SiC and AlN, have shown some promises due to better mechanical, chemical, and tribological properties compared to silicon. SiC thin films are grown at temperatures above 600°C and therefore incompatible with the CMOS thermal budget. Ultrananocrystalline diamond (UNCD), a novel material developed in thin film form at Argonne, exhibits exceptional mechanical, electrical, chemical, and tribological properties that make it excellent for high-performance MEMS/NEMS. Most importantly, UNCD is the only diamond film that can be grown at 400 °C, and retain properties comparable to that of single crystal diamond. In order to exploit excellent properties of UNCD to develop next generation of devices for MEMS and NEMS, however, such devices have to be integrated with CMOS at the wafer level, which will require a materials integration strategy and detailed understanding of degradation mechanism of CMOS upon integration. This paper discusses integration of UNCD with CMOS devices at wafer level (200 mm), which will open new avenues for building CMOS-driven devices for MEMS/NEMS based on UNCD. UNCD films were grown successfully on individual Si-based CMOS chips and on 200 mm CMOS wafers at 400 °C in a plasma-deposition system using microwave-plasma-enhanced chemical vapor deposition with Ar-rich/CH4 gas mixture. The CMOS devices were characterized before and after UNCD deposition. All devices were performing to specifications with acceptable degradation after UNCD deposition and processing. A threshold voltage degradation in the range of 0.08-0.44V and transconductance degradation in the range of 1.5-17% were observed. We also report the on cross-section TEM and RBS studies of the UNCD/CMOS interface and discuss the possible mechanisms responsible for the degradation of CMOS performance.

This work was supported by DARPA under contract MIPR06-W238 and US Department of Energy, BES-Materials Sciences, under contract DE-AC02-06CH11357.

8:20am **MN-TuM2 Optical Excitation of Higher Flexural and Torsional Modes of Nanoelectromechanical Oscillators**, ***B. Ilic***, Cornell University, *S. Krylov,* Tel Aviv University, Israel, *M. Kondratovich, H.G. Craighead*, Cornell University

Excitation of biologically functional micro and nanomechanical structures using optical fields is a recently emerging arena of research that couples the fields of optics, fluidics, electronics and mechanics with potential of generating novel chemical and biological sensors. We present experimental and theoretical elucidation of optical excitation of higher order flexural and torsional modes in resonant nanoelectromechanical systems (NEMS). The modulated optical fields were coupled directly into the NEMS device layer causing amplified mechanical vibrations. Dynamic detection of vibrational characteristics of nanomechanical resonators, fabricated from low-stress silicon nitride and mono-crystalline silicon thin film layers, was accomplished using optical interferrometry. As a model system, 200nm and 250nm thick single crystal silicon cantilevers with dissimilar lengths and widths ranging from 6 to 12µm and 500nm to 1µm, respectively, were fabricated using surface micromachining techniques. We have analyzed the actuation mechanism using finite element modeling, and we found that the dominant actuation mechanism in close proximity of the clamped end was primarily thermal. In contrast, mechanical traveling waves are attributed as possible excitation mechanisms in the far-field regime. Higher order modes of slender cantilevers, calculated using linear Euler-Bernoulli beam model, differed significantly from the measured values. Three dimensional finite element analysis incorporating shear, rotational inertia, deplanation and non-ideal boundary conditions due to the structural undercut, are shown to adequately describe the dynamics of the nanomechanical structures. The quality factor of a particular in-plane harmonic was consistently higher than the transverse mode. The increased dissipation of the out of plane mode was attributed to material and acoustic loss mechanisms.

8:40am **MN-TuM3 Ultrasensitive, Magnet-tipped Cantilevers for Magnetic Resonance Force Microscopy**, ***S.A. Hickman***, *S.R. Garner,* Cornell University, *L.E. Harrell,* United States Military Academy, *B.I. Penkov, S. Kuehn, J.A. Marohn*, Cornell University

Magnetic resonance force microscopy (MRFM) is a technique that may one day allow us to acquire magnetic resonance images of a single molecule - an extremely exciting prospect. To date we have demonstrated a sensitivity of $\sim 10^5$ proton spins. Achieving the attonewton force sensitivity necessary to image single proton spins requires custom-fabricating cantilevers with extreme aspect ratios and mitigating sample-induced dissipation. In MRFM the force exerted on the cantilever, per spin, is proportional to the field gradient from the cantilever's magnetic tip. Achieving single proton sensitivity therefore also requires dramatically reducing magnet size. Unfortunately, all MRFM tips produced to date have been made by manually affixing magnets one-at-a-time to a cantilever. Even if the tips are ion-beam milled, it is difficult to see how they can be made small enough to detect a single proton. We have developed an electron-beam-lithography process for batch fabricating nanoscale tip magnets overhanging the leading edge of ultrasensitive silicon cantilevers. As proof of concept, we will present a 50-nm wide overhanging cobalt magnet fabricated by a process involving electron beam lithography and anisotropic KOH etching, as well as cantilevers with 50-600 nm wide, non-overhanging magnets. Our current goal is to integrate the separate processes of cantilever fabrication and magnet fabrication. With our designed cantilever, we expect a sensitivity of better than 10^3 protons. Even through the process integration challenges are daunting, our successes so far indicate that batch fabricating cantilevers capable of detecting single proton magnetic resonance may indeed be feasible.

9:00am **MN-TuM4 Fabrication of Reliable Through-Silicon via (TSV) Interconnects for 3D Stacking**, ***I.U. Abhulimen***, *A. Kamto, Y. Liu, S. Burkett, L. Schaper*, University of Arkansas

The formation of through-silicon vias (TSVs) provides vertical interconnects that can be used in 3D stacking technology. A sloped via sidewall is essential for conformal coverage in subsequent deposition steps that provide insulation (SiO_2), barrier (TaN) and metal seed (Cu) layers. In this paper, varying via sidewall angles (82º - 90º) are investigated which allow variable degrees of conformal lining of the insulation, barrier and seed layers. The critical thickness of these lining layers that enable conformal coverage of the via sidewall is also investigated. Via insulation is deposited by plasma enhanced chemical vapor deposition (PECVD), while barrier and Cu metal seed layers are deposited by sputtering. A modified Bosch process using a deep reactive ion etch (DRIE) time multiplexing tool is used to create the different via profiles on 125 mm diameter silicon wafers. The cross-sectional view of via lining materials (SiO_2, TaN, and Cu) are examined with both an optical microscope and an environmental scanning electron microscope (ESEM). The via profile is examined using the ESEM. Furthermore, for a fixed via sidewall angle, variable aspect ratios are examined to determine the via profile that can be conformally lined and filled by Cu electroplating without any voids. The aspect ratios of the vias under study are 3, 4, 5, 6, and 8. Electrical performance and via integrity of the TSV process is also reported. Test structures are created during TSV processing that allow for a thorough study of interconnect reliability. This includes tests for via chain continuity, single via resistance, and via isolation.

9:20am **MN-TuM5 Micro and Nano Electro-Mechanical Systems: Technology for Engineering Metamorphosis**, ***A. Lal***, DARPA **INVITED**

The core of MEMS technology is the capability to form chip-integrated micro beams, cantilevers, and plates. DARPA has mined MEMS technology since the early 1990s in an effort to provide increased performance and functionality to integrated circuits. MEMS allows one to use reduced mass for increased resonance frequencies in micro-resonators; craft long and thin high aspect ratio structures for high thermal resistances; and generate huge surface-to-volume ratios for increased interaction with the environment. MEMS technology changes systems so rapidly that there is less of an evolution, and more of a metamorphosis; gradual growth is replaced by complete transformation. This is especially true in the last decade of MEMS, where integration over multiple MEMS devices is finally making the Systems part of MEMS closer to reality. This talk will describe scaling issues in realizing MEMS systems with a particular emphasis on micropackaging, new materials, and design principles on reliability of MEMS and NEMS subcomponents. The successful realization of the chip-scale atomic clock, which is a multiphysics microsystem, will be described in the context of MEMS thermal isolation.

10:40am **MN-TuM9 Self-Packaged Micro Fluorescence Detection Systems**, ***S.S. Kim***, *E. Saeedi*, University of Washington, *D.R. Meldrum*, Arizona State University, *B.A. Parviz*, University of Washington

We present a self-packaging micro-fluorescence biosensor chip which assembles fully functional separately fabricated micro-components onto a common substrate. The essential components of the fluorescence based sensor are: 1) an excitation light source, and 2) a means to detect fluorescence emission. AlGaAs LEDs and silicon pn-junction photosensors are self-assembled onto a glass template to meet these requirements. The micro-components range in size from 100 to 300 microns and were specifically designed to optimize and aid in the self-assembly process. The powder-like collection of micro-components are suspended in a liquid and flowed onto a glass substrate. They self-assemble into their receptor site locations through gravity, shape recognition, and capillary forces, resulting in an array of individually addressable fluorescence detection units. Self-assembly provides a number key advantages over traditional packaging and fabrication approaches. First and foremost, it allows us to integrate micron-scale heterogeneous materials together onto a common substrate. This gives us a unique ability to have all the essential components of a fluorescence detection system on chip, without the need for an external scanner device or benchtop system. Second, the self-assembly process is parallel in nature and benefits from economies of scale. Large arrays of devices can be packaged at the same time. We have demonstrated the packaging of a 10K element array onto a plastic substrate. Thousands of individually addressable fluorescence detection units are possible allowing for data acquisition of a large number of samples simultaneously without being limited by the field of view of the optics. Third, self-assembly gives us the ability to use low cost substrates such as glass and plastics. Only small amounts of semiconductor materials are used where they are needed, reducing the total amount used for each device. This has the potential to drive down the overall cost per device low enough to make them disposable, opening new doors to biosensing applicaitons which require a fluorescence detection platform which is both portable and disposable. Potential applications include point-of-care diagnostics, bioterrorism, food/industrial testing, HIV/STD testing in developing countries, and so on. The benefits of mature fluorescence based assays could be realized on a portable and disposable chip-level platform using this approach to device packaging.

11:00am **MN-TuM10 Bi-Directional Transport of Ultra-Low Volume Droplets Using Capacitive Sensing**, ***P. Dykstra***, *X.Z. Fan, M. Mischiati, L.A. Mosher, N.P. Siwak, R. Ghodssi*, University of Maryland

MEMS cantilever sensors are utilized to detect trace quantities of specific agents in liquid. One of the most common methods to deliver the fluid is by flooding the cantilever's surroundings, but this often leads to stiction-related failures due to surface tension. We present a bi-directional microfluidic device for analyte delivery to MEMS sensors. Our device can deliver a picoliter-sized droplet to the cantilever sensor and then retract the droplet without wetting the entire sensor, thus eliminating this problem. The most commonly used drop-on-demand technology through a nozzle, exploited for inkjet printing and for the selective deposition of polymers, is based on the release of an entire droplet over the target. Our design proposes to eject only enough to reach the target area, without breaking the droplet from the bulk of the liquid. This allows the droplet to be retracted by reversing the flow, thus achieving bi-directional transport of ultra low volumes of liquid. Droplet control is facilitated by position-sensing from a capacitive sensor. As the droplet lowers, a change in capacitance is measured by a sensor electrode located below the nozzle. Our microfluidic system, consisting of packaging, micronozzle, and microsensor wafers, was fabricated using conventional MEMS techniques. The through-etched micronozzle was diced and aligned to the microsensor wafer using peg-in-hole (SU-8 pegs in etched silicon holes) assembly. This precisely aligns the nozzle over a gold electrode on the sensor wafer. Capacitance is measured between the nozzle die itself and the gold electrode using an Agilent CV meter. The liquid is administered using a syringe pump at a constant flow rate. Our initial results show that the capacitance slowly rises as the droplet is formed. A significant change in capacitance occurs when the droplet makes contact with the microsensor. A complete analysis of droplet formation measurements, by way of capacitive sensing, will be presented. Transport will be characterized to enable the integration of our device with any MEMS sensor.

11:20am **MN-TuM11 Microfluidic Transport Control Using Remotely Powered Semiconductor Diodes**, ***D.N. Petsev***, University of New Mexico, *S.T. Chang, O.D. Velev*, North Carolina State University, *V.N. Paunov*, University of Hull, UK

The precise control of fluid transport in microchannels is of paramount importance for the successful design and operation of fluidic devices. We have recently demonstrated[1] that using miniature diodes embedded in the walls of fluidic microchannels in combination with AC field is a very simple and convenient tool to manipulate the flows in microchannels. Our focus is on two particular problems briefly described below Mixing. Due to the low Reynolds number of microflows, mixing of components is a real challenge. Due to the laminar character of the flow different solution tend to flow side by side and the only way for solutes to cross the streamlines is by diffusion. Using properly (anti-parallel) oriented diodes, placed alongside the channel walls, allows generating a vortex fluid motion by simply turning on a properly connected Alternate Current (AC) field source. Such vortex dramatically improves the mixing in the microfluidic device. Another advantage of this approach is that such diode mixer can easily be turned on and off through the AC field power source. Separation. Using parallel oriented diodes and a combination of AC and Direct Current (DC) fields in a loop-shaped channel allows complete decoupling of the fluid electroosmosis from the analyte electrophoresis. Balancing the electrophoretic and convective forces on the different analytes allows for a very easy and efficient separation. The parallel oriented pair of diodes, powered by the applied AC field, acts as a miniature pump and drives the fluid in a circulatory motion in the loop shaped channel. Any charged analytes, however, will not migrate in the AC field. Applying DC field to the fluidic device will not drive the fluid motion because this particular design (closed symmetric loop) cancels the electroosmotic driving force. Hence, combining the two fields (AC and DC) allows decoupling of the fluid flow from the particle electrophoretic migration.

[1]S. T. Chang, V. N. Paunov, D. N. Petsev and O. D. Velev, "Self-Propelling Microdevices and Microfluidic Pumps Based on Remoutely Powered Miniature Semiconductor Diodes, Nature Materials, 6 (2007) p. 235.

11:40am **MN-TuM12 Towards Feedback Control with Integrated Position Sensing in Micromachines**, ***M.I. Beyaz***, *N. Ghalichechian, A. Modafe, R. Ghodssi*, University of Maryland

Micromachines require closed loop systems to facilitate synchronization and yield maximum performance. However, little effort has been spent on implementing feedback control in these devices. We present for the first time the design, fabrication and testing of an integrated feedback control system for a synchronous electrostatic micromotor. This system aims to synchronize the mechanical motion and the electrical excitation to improve stability and performance. The micromotor is composed of a stator and a movable slider supported on microball bearings. Interdigitated photodiodes are located on the stator to detect the position of the slider moving relative to the stator electrodes. Through holes, created by deep reactive ion etching, are aligned with the poles on the slider. This allows light, provided from the top, to reach the photodiodes on the stator. The design is such that the optical sensing of slider position is achieved by simultaneous alignment of pole-electrode and hole-photodiode pairs, causing an increase in photodiode current. The change in current is sensed and the appropriate voltages are applied to stator electrodes by a feedback circuit. The designed photodiodes have been implemented on n-type 20 Ω-cm silicon wafers. The fabrication consists of etching the native oxide on the wafer, aluminum sputtering and wet etching. Prior to the integration of the photodiodes with the micromotor, a test setup was built to verify the feasibility of the feedback system. In this setup the stator, on which only the photodiodes are fabricated, is fixed to an oscillating platform driven sinusoidally at 5 Hz at an amplitude of 1.6 mm. The slider is kept stationary and a light source is provided from the top. Resulting photodiode current depends on how much light it receives through the holes. The motion of the stator is monitored by the photodiode response that is in the form of a triangular wave. Each peak on the waveform corresponds to a complete alignment between the photodiode and a hole on the slider. Using this peak detection, the instantaneous platform speed is calculated showing good agreement with the applied sinusoidal motion with an R^2 value of 0.925. This work verifies the feasibility of the feedback system for the given micromotor to achieve higher speeds and to stand varying load conditions. Detailed fabrication steps and experimental results of the micromotor with the control system will be presented.

12:00pm **MN-TuM13 An Adaptive Feedback Control Circuit for Resonator Sensors**, ***X.Z. Fan***, *N.P. Siwak, R. Ghodssi*, University of Maryland

Integration of smart electronics with MEMS sensors will enable systems to be versatile, compact, and portable. MEMS resonator sensors are powerful tools for the detection of target analytes due to the high sensitivity of resonant frequency to absorbed mass. We present an adaptive feedback control circuit to detect and trace the resonant frequency of MEMS resonator sensors. The purpose of our feedback circuit is its integration with a fully developed III-V optical resonator system for chemical and biological sensors, facilitating testing and data acquisition. Feedback circuits with similar functions, such as self-excitation systems, have been reported before in literature. These systems, however, require phase and amplitude compensation stages that require separate designs for each resonator measured. Our feedback circuit utilizes a hill climbing algorithm which is valid for any resonator sensor that exhibits any range of resonant frequency, thus broadening the applicability of the circuit. The hill climbing algorithm sweeps the driving frequency searching for maximum cantilever response. The algorithm is implemented using a four-stage CMOS circuit consisting of an amplitude detector, a differentiator, a digital logic circuit, and a voltage controlled oscillator (VCO). The feedback circuit receives the displacement output of the resonator and supplies the actuation signal to the resonator from the VCO output. Utilizing the hill climbing algorithm, the resonator is driven at its resonant frequency. By monitoring the VCO input voltage, the resonant frequency with respect to time can be measured. We have confirmed the adaptability of the design of the circuit with initial testing results. The results have demonstrated that the maximum amplitude of an input signal can be detected with input frequencies ranging from 100 KHz to 500 KHz. This range is only limited by the frequency response of the CMOS components. A delay of 3 ms was observed between the input and output signal of the circuit, which is acceptable due to a significantly larger sensor time constant. We will present the test results of the combined circuit with indium phosphide MEMS cantilever sensors. The flexibility of the circuit and its improved capabilities over conventional measurement circuits will be demonstrated.

Authors Index

Bold page numbers indicate the presenter