The Science of Micro-Electro-Mechanical Systems Topical Conference
Room 324/325 - Session MM+PS-MoM
MEMS Processing and Deep Si Etch Technology
Moderator: L.M. Miller, Jet Propulsion Laboratory

8:20am **MM+PS-MoM1 Overcoming Barriers to MEMS Prototyping and Production***, **D.A. Koester**, K.W. Markus,* MCNC **INVITED**

As MEMS continues to grow and expand into new markets, there continues to be a need for low cost proof-of-concept and prototype fabrication. For the past 6 years, MCNC has provided a number of services designed to provide the domestic MEMS community with an array of fabrication and design services intended to help overcome the cost and accessibility barriers to MEMS product development. The cornerstone of this DARPA-supported program, called the MEMS Technology Network (TechNet), is the Multi-User MEMS Processes (MUMPs). MUMPs is a three-polysilicon surface micromachining process offered in a multi-user environment to offset the high cost of fabrication. Since its inception in January '92, MUMPs has fabricated over 1000 designs for more than 140 different R&D groups and has been available to the world-wide community since July of '98. The SmartMUMPS program enables electronics integration of MUMPs by way of flip chip of a standard ASIC designed with a variety of sensing blocks. LIGA technology is also made available through the program. The MEMS Technology Network also provides a spectrum of custom services to the community including deep silicon RIE, backside patterning, stock substrates and access to a Microcosm MEMCAD 4.0 seat.

9:00am **MM+PS-MoM3 Materials, Process, and Integration Issues in SiC MEMS***, **M. Mehregany**,* Case Western Reserve University **INVITED**

SiC MEMS technology holds great promise for applications which are characterized by presence of harsh environments (e.g., high temperatures, large number of vibrational cycles, erosive flows, and corrosive media). Historically, SiC research has focused on the materials and processes needed for high-temperature and high-power microelectronics. These devices require high-quality single crystal films and substrates, which lead most researchers to use 6H-SiC, since nearly defect-free wafers and epitaxial films are available. Unfortunately, high quality comes at a high price; 6H-SiC wafers are very expensive and are available only in small wafer diameters. Thus, applications for 6H-SiC devices are limited to areas which can absorb such high costs, such as (military) aircraft and spacecraft. Our work has been motivated by the necessity to develop a low-cost SiC MEMS technology to penetrate a much more diverse set of markets, including for example automotive. Additionally, we have been motivated to leverage off of the latest fabrication process technologies available from Si to push the SiC MEMS technology further, faster. As a result, we have pursued large-area substrates, i.e., 3C-SiC on Si. Unlike 6H-SiC, 3C-SiC is the only SiC polytype which can be heteroepitaxially grown on Si substrates. Heteroepitaxy on Si gives 3C-SiC a distinct advantage over 6H-SiC in terms of batch fabrication, since high quality, large-area Si substrates are readily available and comparatively very inexpensive. We have pursued the development of bulk and surface micromachining processes using 3C-SiC and poly-SiC, respectively. Heteroepitaxy of 3C-SiC on Si is attractive to MEMS not only for batch fabrication, but also for bulk micromachining. In fact, SiC is undoubtedly an excellent etch stop material for Si bulk micromachining, since Si anisotropic etchants such as KOH and EDP are impervious to SiC. We have used Si bulk micromachining techniques to fabricate a multitude of 3C-SiC structures, ranging from diaphragms for mechanical properties studies, pressure sensors, and optical transmission windows, to cantilever beams and torsional micromechanical structures. Bulk micromachining of 6H-SiC has been demonstrated by others, however the process is much more complicated and the dimensional control and etch stop capabilities are limited at this time. Unlike electronics applications which require high-quality single crystal films, MEMS is much more flexible in that structures can be fabricated from polycrystalline films. SiC MEMS is no exception. We have developed poly-SiC as a basic structural material for SiC MEMS. We have deposited APCVD poly-SiC films atop polysilicon and silicon dioxide sacrificial films on 4 inch diameter Si wafers. We have demonstrated SiC surface micromachining processes, and these have been used to fabricate the first SiC lateral resonant structures. These devices tested at temperatures up to 900C outperformed polysilicon resonators of like geometry with respect to high temperature capability. Of course, the surface micromachining technology using poly-SiC would be extendable to 6H- and 4H-SiC substrate technology, as well as integration with SiC electronics on these substrates. An overview of materials, process, and integration issues in SiC MEMS will be presented, including current device examples.

9:40am **MM+PS-MoM5 Thermally-Actuated Micro-Beam for Large In-Plane Mechanical Deflections***, **E.S. Kolesar**, P.B. Allen, J.T. Howard, J.W. Wilken,* Texas Christian University

Numerous electrically-driven microactuators have been investigated for positioning individual elements in microelectromechanical systems (MEMS). The most common modes of actuation are electrostatic, magnetostatic, piezoelectric and thermal expansion. Unfortunately, the forces produced by electrostatic and magnetostatic actuators tend to be small, and to achieve large displacements, it is necessary to either apply a large voltage or operate the devices in a resonant mode. On the other hand, piezoelectric and thermal expansion actuators can be configured to produce large forces and large displacements. Unfortunately, piezoelectric materials are not routinely supported in the fabrication processes offered by commercial MEMS foundries. Consequently, these limitations have focused attention on thermally-actuated devices for generating the large forces and displacements frequently required to position and assemble complex MEMS. This research focuses on the design, finite element analysis and experimental performance evaluation of a MEMS thermally-actuated beam. The motivation is to present a unified description of the behavior of the thermal beam so that it can be adapted to a variety of applications in the microsensor and microactuator arenas. A MEMS polysilicon thermally-actuated beam uses resistive (Joule) heating to generate thermal expansion and movement. When current is passed through the actuator from anchor-to-anchor, the larger current density in the released "hot" arm causes it to heat and expand more than the "cold" arm. Since both arms are joined at their free (released) ends, the actuator tip is forced to move in an arc-like pattern. Removing the current from the device allows it to return to its equilibrium state. To be a useful MEMS device, a thermally-actuated beam will need to produce incremental in-plane mechanical beam tip deflections that span 0-10 microns while generating force magnitudes greater than 10 micro-newtons. The thermally-actuated beam design was accomplished with the L-Edit software program, and the devices were fabricated using the Multi-User Microelectromechanical Systems (MEMS) Process (MUMPs) foundry at the Microelectronics Center of North Carolina (MCNC). A finite element modeling analysis was accomplished with the IntelliCAD computer program. This CAD software incorporates an MCNC fabrication process description file that generates a 3-D solid model of the thermal beam. Additionally, the thermal and electromechanical finite element analyses predicted beam tip deflections and forces consistent with experimental observations. When the "hot" arm's temperature is 600@degree@C (Joule heating), the resulting beam tip deflection is 4.55 microns. For a beam tip force of 14 micro-newtons, the displacement was calculated to be 12.9 microns. The resonant frequency, without damping, was calculated to be 74.7 kHz. The MEMS thermally-actuated beam performance was also experimentally characterized. When the drive voltage was varied between 0 and 8 VDC, tip deflections spanning 0-7 microns were observed. The corresponding tip forces spanned 0-12 micro-newtons. The resonant frequency in ambient air was 68.7 kHz. A measure of the reliability of the thermal beam was established to be greater than 2 million cycles, when continuously operated with a 60 Hz, 4-volt amplitude square wave.

10:00am **MM+PS-MoM6 Development of a Micro EHD Pump Using Laser Micro-machining***, **C.C. Wong**, D. Chu, D.R. Adkins,* Sandia National Laboratories

At Sandia, we are developing an active cooling MEMS device for microelectronics applications. This integrated device will incorporate a micro-pump, temperature sensors, micro-channels, and heat exchanger components into a single unit. The first step of this development is to rapidly prototype a micro-pump based on electro-hydrodynamic (EHD) injection principle using laser micro-machining technology. Two initial micro-pumps designs have examined for full fabrication. The first design has two silicon parts stacked vertically on top of each other. Gold is deposited on one side of each stacked plate to serve as electrodes for the electro-hydrodynamic pumping. A Nd:YAG laser is used to drill an array of circular holes in the "well" region of both silicon parts, leaving an open pathway for fluid movement. The Nd:YAG laser is preferred for our fabrication process than excimer laser because of a smaller up-front cost and a less potential environment, safety, and health concern with toxic gases when using excimer laser. Moreover the Nd:YAG laser will allow the operational wavelength to be converted to several frequencies from the near infrared portion of the spectra (1064 nm @lambda@) to the ultraviolet portion of the spectra (266 nm @lambda@). After the holes are drilled, the silicon parts are aligned and bonded together with polyimide, thus becoming a EHD pump. Fluid flow has been observed when an electric voltage is applied across the electrodes. The newest design has the silicon parts which contain the flow grid oriented "back-to-back" and bonded together. This "back-to-back" design has a shorter grid distance between the anode and cathode plates so that a smaller voltage is required for pumping. A thinned Si spacer was used to maintain consistent grid distance between plates. Experimental results have demonstrated that this EHD micro-pump can generate a pressure head of about 287 Pa with an applied voltage of 120 V. @FootnoteText@ This work was supported by the US DOE under Contract DE-AC04-94AL85000.

10:20am **MM+PS-MoM7 Laminated Plastic Microfluidic Components for Biological and Chemical Systems***, **P.M. Martin**, D.W. Matson, W.D. Bennett, D.J. Hammerstrom,* Battelle Pacific Northwest National Laboratory

Laminated plastic microfluidic components are being developed for biological testing systems and chemical sensors. Applications include a DNA thermal cycler, DNA analytical systems, electrophoretic flow systems, dialysis systems, blood sampling, and metal sensors for ground water. This paper describes fabrication processes developed for these plastic microscale components. Most of the components have a stacked architecture, the fluid flows, or is pumped through as many as nine laminated functional levels. Functions include mixing, reaction, and detector channels, reservoirs, and detector electronics. Polyimide, PMMA, and polycarbonate materials with thicknesses between 25 and 100 µm are used to construct the components. This makes the components low cost, inert to many biological fluids and chemicals, and disposable. The components are fabricated by excimer laser micromachining the microchannel patterns and microstructures in the various laminates. In some cases, micropumps are integrated into these components to move the fluids. Vias and interconnects are also cut by the laser, and integrated with micropumps. The laminates are sealed and bonded by adhesive and thermal processes, and are leak tight. The parts withstand pressures as high as 790 kPa. Typical channel widths were 50 µm to 100 µm, with aspect ratios near 5. Performance data will be presented for the DNA thermal cycler and a voltammic chromium metal sensor.

10:40am **MM+PS-MoM8 Deep Anisotropic Etching of Silicon***, **S. Aachboun**, P. Ranson,* University of Orleans, CNRS, France

Dry etching of silicon has been largely studied in HDP reactors for many applications such as in Microelectronics. Moreover, deep etching is a relatively new approach that can be widely used in MEMS in the near future. However, as required depths increase, the etch rate and the anisotropy decrease radically with the Aspect Ratio (width/depth). We are interested in etching very deep anisotropic trenches (~100µm) with high Aspect Ratios (~50) and high etch rates (~5µm/mn). A HDP Helicon reactor using a SF6/O2 chemistry and a cryogenic chuck has been used for etching very narrow trenches and holes from 1,2µm to 10µm of width on n-type Si wafers with a SiO2 mask. The first results of this investigation show significant features that demonstrate the feasabilty of this method. Two microns width trenches have been etched over a depth of 50µm at 3µm/mn . The resulting profiles are highly anisotropic and the selectivity Si/SiO2 is over 500. A DOE has been set in order to evaluate the effects of the different parameters and, in order to monitor the plasma and improve the features, Langmuir probe, optical spectrometer and mass spectrometer investigations are planned.

11:00am **MM+PS-MoM9 Application of the Footing Effect in the Microfabrication of Self-Aligned, Free-Standing Structures***, **A.A. Ayon**, K. Ishihara, R. Braff, H. Sawin, M.A. Schmidt,* Massachusetts Institute of Technology

The footing or notching effect is observed when dry etching silicon or polysilicon layers on buried dielectric films.@footnote 1@ This effect is usually considered an undesirable feature for most applications, although it is frequently small in conventional reactive ion etching (RIE) tools due to the low density of the plasmas utilized. However, with the new generation of inductively coupled plasma etching tools the notching effect can extend laterally several microns depending not only on operating conditions but also on the aspect ratio@footnote 2@ and extent of overetching time. The suppression of this effect depends in a critical manner on achieving a balance between etching and deposition of passivating films.@footnote 3@ Deviations from such balance promote the appearance of grass or even excessive deposition of passivating films. We review the dependence of footing effect on etching conditions in a time multiplexed deep etcher (TMDE) and suggest specific operating conditions to preclude the appearance of notching even when overetching for as much as 85%. Additionally, we introduce the application of the footing effect in the microfabrication of free-standing structures, by demonstrating the micromachining of self-aligned, wafer-free electrostatic actuators for which etching, releasing, ashing and passivating (dielectric isolation) were done in the same piece of equipment. All processes needed to produce cantilevered structures are done in situ using VLSI compatible plasma chemistries only. The measured pull-in voltage for a 1000 µm cantilevered beam, of the order of 85 V, agrees with predicted values. The novel low-temperature, soft-mask scheme presented here, is compatible with other VLSI processes and can be easily integrated in the microfabrication of intelligent sensors and actuators. This robust new concept allows unparalleled fabrication simplicity while permitting the fabrication of sctructures and devices in an efficient and timely fashion. Electrostatic actuators with or without interdigitated fingers, valves, pumps and relays, to name but a few, are applications that immediately benefit with this technique. @FootnoteText@ @footnote 1@G. S. Hwang and K. P. Giapis, J. Vac. Sci. Technol., B 15 (70) 1997. @footnote 2@T. Nozawa, T. Kinoshita, T. Nishizuka, A. Naral, T. Inoue and A. Nakaue, Jpn. J. Appl. Phys., 34 (2107) 1995. @footnote 3@J. P. Chang, Ph. D. Thesis, Massachusetts Institute of Technology, 1997.

11:20am **MM+PS-MoM10 Test Structure Experiments and Modeling of Very Deep Dry Etching Processes for MEMS Applications***, **S. Abdollahi-Alibeik**, J.P. McVittie, K.C. Saraswat,* Stanford University

One successful approach for getting the desired high (~ 4µmm/min) etch rates for MEMS device fabrication is separating the etch and passivation steps in order to eliminate the interference in chemistry. The focus of this work is on the understanding and modeling of the very deep (>100µmm) trench etch process based on this approach. Experiments were done to investigate different aspects of both deposition and etch phases. C@sub 4@F@sub 8@ gas was used for the deposition phase. The deposited material is a CF@sub x@ polymer. It was observed that the deposition rate is highly dependent on the ion flux and ion energy received by the surface. This can be modeled as an increase in the effective sticking probability of the deposition species. While polymer deposition in an overhang test structure is not that conformal, the rate of passivation does not change when the trenches become very deep. The above model and the fact that the trench sidewalls receive little ion flux can explain this discrepancy. In addition, ion reflection also appears to be important since sidewall deposition shows a dependence on the opposite sidewall. For the etch phase SF@sub 6@ gas was used. Lag experiments show that the transport of the etchant species down the trenches depends on the deposition phase. The lag was higher for a larger ratio of etching to deposition time. The fact that ion bombardment of the CF@sub x@ polymer releases F atoms can be the reason for this change in lag behavior. Incorporation of the model into the SPEEDIE profile simulator will be shown.

11:40am **MM+PS-MoM11 Pattern Shape Effects and Artefacts in Deep Silicon Etching***, **J. Kiihamaki**, S. Franssila,* VTT Electronics, Finland

Deep silicon etching in inductively coupled plasma (ICP) reactor offers high etch rate, nearly vertical profile, and good selectivity against most common masking materials. Crystal orientation independent ICP etching can replace area consuming KOH wet etch in many micromechanical applications. We have etched various test structures with patterns of different sizes and shapes, using different etch chemistries and etch times. The widths of etched patterns range from submicron to over 100 µm, the etched depths were up to 500 µm. Long narrow features are etched faster than wide short features, indicating three dimensional nature of RIE-lag. Aspect ratio dependent etch rate is also present, further complicating design rule - process interactions. The difference in etch rate of a rectangular hole with respect to a trench of same width increases with aspect ratio and can be up to 20%. Typically narrow trenches have positive angled sidewalls and as trenches get wider the profile turns into retrograde, which implies serious limitations to device design. Positive or vertical profiles can be achieved if etch rate is lowered to 1-2 µm/min. Amount of etchable area also affects profile. Coalescence of closely spaced trenches into a larger feature (due to retrograde profile and/or undercutting) causes both etch rate and profile to change. Large area structures connected to narrow trenches assist the etching of the narrow trenches over considerable distances. To fully utilise the benefits of ICP etching, the design rules must be tailored for each application, because of various pattern shape effects.

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