Microelectromechanical Systems (MEMS)
Room 320 - Session MM-TuA

Fabrication and Characterization of MEMS Devices

Moderator: C.B. Freidhoff, Northrop Grumman

2:00pm **MM-TuA1 Development of a Deep Phase Fresnel Lens in Silicon***,* ***B. Morgan****, C.M. Waits,* University of Maryland, College Park*; J. Krizmanic,* NASA - Goddard Spaceflight Center*; R. Ghodssi,* University of Maryland, College Park

Astronomical observations at Gamma and hard X-ray energies are presently hindered by instruments with low sensitivity and poor angular resolution. Fresnel Zone Plates and their derivatives, could achieve higher sensitivity and greater angular resolution.@footnote 1@ For ground testing of a Phase Fresnel Lens (PFL), lateral dimensions of each lens feature must be on the order of 10 µm, while vertical dimensions must be >20 µm, both a natural fit for MEMS processing. Silicon, the standard material used in MEMS, has low absorption of Gamma and X-ray radiation, making it a good material choice for the fabrication of a PFL for ground testing. Gray-scale technology was selected as the fabrication method for developing such a lens because of two main advantages: (1) the multiple heights required for increased efficiency may be fabricated without alignment, and (2) Deep Reactive Ion Etching (DRIE) with precise selectivity control enables the fabrication of deep (>20 µm) silicon lenses. Multiple PFL's, with diameter >1.6mm and varying heights, have been successfully fabricated in silicon. The optimization of gray-scale lithography processing for large-scale structures was realized through the use of a custom calibration mask. Advanced gray-scale optical mask design allows the fabrication of small gray level geometries over a large area, enabling precise profile control to maximize lens efficiency. Depending on target photon energy, etch depths required to produce the appropriate phase shift in silicon have been between 20 and 100 µm. Highly accurate vertical dimension control is also necessary to ensure the proper interference pattern at the lens focus. Therefore, PFL height was controlled by finely tuning etch selectivity during DRIE, which adjusts the scaling factor between photoresist and silicon, and provides the appropriate PFL profile in silicon. @FootnoteText@ @footnote 1@G.K. Skinner, Astronomy & Astrophysics, v.375, no.2, 2001, p.691-700.

2:20pm **MM-TuA2 Fabrication and Characterization of a Capacitive Micromachined Shunt Switch***,* ***S.L. Firebaugh****,* United States Naval Academy*; H.K. Charles, Jr., R.L. Edwards, A.C. Keeney, S.F. Wilderson,* Johns Hopkins University

Microelectromechanical switches offer many advantages over solid-state devices, including greater linearity, increased isolation and lower insertion loss.@footnote 1-5@ One disadvantage of such switches is that they require high actuation voltages (20-100 V), leading to problems with dielectric charging and system integration. Furthermore, when reducing the actuation voltage one must consider the dependence of power handling capability on actuation voltage.@footnote 6@ This paper describes the design, fabrication and testing of a shunt switch@footnote 3,4@ based on a bridge suspended over a coplanar waveguide. When a sufficient DC voltage is applied the bridge pulls down towards the signal line, creating a high-frequency short circuit and causing the signal to reflect back towards the source, blocking transmission. The switch is used as a test vehicle to explore the effects of bridge shape on performance, as well as to investigate the limits of micromachined switches. A common problem for MEMS switch developers is obtaining equipment to test device characteristics such as power handling limits on a wafer probe station. In this work, standard microwave connectors and equipment are facilitated by a custom test fixture. The pull-in effect is studied in detail, as well as methods for switching the device while avoiding dielectric charging effects and maintaining reasonable power handling levels. @FootnoteText@ @footnote 1@ C.T.C. Nguyen et al., Proc. IEEE, vol. 86, no. 8, pp. 1756-1768, August 1998.@footnote 2@ J.J. Yao, J. Micromech. Microeng., vol. 10, pp. R9-R38, 2000.@footnote 3@ Z.J. Yao et al., IEEE J. Microelectromech. Syst., vol. 8, no. 2, pp. 129-134, 1999. @footnote 4@ J.B. Muldavin and G.M.Rebeiz, IEEE Trans. Microwave Theory and Tech., vol. 48, no. 6, pp. 1045-1052, June 2000.@footnote 5@ D. Hyman et al., Electron. Lett., vol. 35, no. 3, pp. 224-226, February 1999.@footnote 6@ B. Pillans et al., 2002 IEEE MTT-S Int. Microwave Symp. Dig., pp. 329-332.

2:40pm **MM-TuA3 Design and Process Integration of an Electric Induction Micromotor***,* ***C. Livermore****, J.L. Steyn,* Massachusetts Institute of Technology*; J.U. Yoon, A. Forte,* MIT Lincoln Laboratory*; R. Khanna,* Massachusetts Institute of Technology*; T. Lyszczarz,* MIT Lincoln Laboratory*; S.D. Umans, J.H. Lang,* Massachusetts Institute of Technology **INVITED**

We present the development of a millimeter-scale electric induction machine designed to output Watt-level power for portable power applications. The micromotor comprises a stack of five micromachined silicon wafers. A 4 mm spinning silicon rotor disk is encapsulated within the stack; facing the spinning rotor is a six-phase electric stator. Mechanical-electrical power conversion is accomplished by the interaction of the stator potential with induced charges on the rotor. To operate at high power levels, the micromotor must operate under extreme conditions: high speed rotation (near one million rpm), high voltages (300 V across 3 µm to 4 µm gaps), and high electric frequencies (about 1.5 MHz). These requirements in turn place stringent requirements on the device design and fabrication flow: low electric losses, excellent resistance to electric breakdown, and essentially leak-free wafer bonds among the five silicon wafers. This presentation describes the approaches that are used to meet these requirements simultaneously in a complete, functional device. A thick oxide liftoff process is used to embed islands of oxide in the silicon substrate under the electric elements to reduce stray capacitance and electric losses. The island structure also minimizes overall bow from the stressed films, making wafer bonding possible. The stator's two-level interconnected electric elements are made of platinum and fabricated by a liftoff process. The platinum electrodes and interconnects reduce line resistance, minimize ohmic losses, and provide a smooth, break-down resistant line shape.@footnote 1@ @FootnoteText@ @footnote 1@ The Lincoln Laboratory portion of this work was sponsored by the Defense Advanced Research Projects Agency. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the Department of Defense.

3:20pm **MM-TuA5 Microfabrication of a Pressure Sensor Array Using 3D Integration Technology***, M. Khbeis,* Laboratory for Physical Sciences*;* ***X. Tan****,* University of Maryland*; G. Metze,* Laboratory for Physical Sciences*; R. Ghodssi,* University of Maryland

A novel microfabrication approach that enables successful integration of a piezoresistive pressure sensor array on an airfoil for detection of micro-scale turbulent vortices is presented. These sensor arrays will be used to study the dynamics of turbulent air flow with the ultimate goal of reducing drag on aircraft. Minimization of surface undulations on the sensor is required to avoid generating additional air turbulence. Therefore it is essential to implement an enabling fabrication approach that eliminates the dependence on topside electrical connections. We have developed a 3D integrative process to provide backside interconnections, while maintaining the specified 200µm sensor element pitch. This 3D fabrication effort incorporates several advanced process technologies including: low temperature SiO@sub 2@-to-Si wafer bonding (<250°C), bulk wafer thinning (to 20µm), high-aspect ratio (HAR 20:1) Si and SiO@sub 2@ etching using m=0 resonant induction (M0RI), and HAR (10-15:1) metallization using high pressure Aluminum reflow. This integrative process will facilitate vertical stacking of multiple device components on different layers, allowing the integration of MEMS and microelectronic devices for the realization of Small Smart Systems (SSS). Process developments and preliminary experimental results are presented.

3:40pm **MM-TuA6 Simulation of Field Emission-based Pressure Sensors***,* ***A.M. Nair****, N. Badi, A. Bensaoula,* University of Houston

This paper reports on simulating the moving part of a field emission-based pressure sensor. The device is comprised of a membrane made of silicon or other stiffer materials acting as the anode of a device comprised of a fixed flat cold cathode emitter. This is achieved by modeling the deflection and mechanical stress of a diaphragm of varying geometry under selected input pressures. Realistic field emission characteristics from our boron nitride and carbon nitride cold cathodes@footnote 1@ were used to model the current density distribution in the deflected diaphragm. The total current output was achieved by integrating the current density over the entire diaphragm area as a function of membrane bending due to external pressure. Results show that simple and reliable field emission devices can be designed to yield extremely sensitive pressure sensors but their characteristics are critically dependent on the specific geometry. Simulation data will be presented for devices with geometries similar to those being fabricated in our laboratory. @FootnoteText@@footnote

1@N. Badi, A. Tempez, D. Starikov, A. Bensaoula, V.P.Ageev, A. Karabutov, M.V. Ugarov, V. Frolov, E. Loubnin, K. Waters and A. Shultz, "Field Emission from as-grown and Surface Modified BN and CN Thin Films" J. Vac. Soc.Technol. A 17, 1191 (1999). Acknowledgment: This material is based upon work supported by the National Science Foundation under Grant No. 0010100

4:00pm **MM-TuA7 Nanotribological Characterization of Digital Micromirror Devices using Atomic Force Microscopy***, **H. Liu**, B. Bhushan,* Ohio State University

Texas Instruments' Digital Micromirror Device (DMD) comprises an array of fast digital micromirrors, monolithically integrated onto and controlled by an underlying silicon memory chip.@footnote 1@ It is one of the few success stories in the emerging field of microelectromechanical systems (MEMS). In this study, atomic force microscopy (AFM) has been used to characterize the elements of the mirror structure of the DMD. AFM images of the mirror, hinge and yoke, and metal arrays are characterized. An AFM methodology was developed to identify and remove mirrors of interest. The surface roughness and adhesion properties of contacting surfaces were extensively studied. The influence of relative humidity and temperature on the behavior of the DMD was also investigated. Potential mechanisms for stiction accrual@footnote 2@ are discussed in light of the findings. @FootnoteText@ @footnote 1@L.J. Hornbeck, MRS Bulletin, 26, 325(2001) @footnote 2@B. Bhushan, (ed.), Tribology Issues and Opportunities in MEMS, (Kluwer Academic, Dordrecht, Netherlands, 1998).

4:20pm **MM-TuA8 PZT Dry Etching using ICP Etcher for MEMS Devices***, **M. Dubey**, R.G. Polcawich, E. Zakar, J. Pulskamp, A.E. Wickenden, L.J. Currano,* U.S. Army Research Laboratory

Piezoelectric Lead Zirconate Titanate (PZT) thin films deposited on platinized silicon substrates were reactively ion etched using an inductively coupled plasma (ICP) etching system. Etch rates for PZT, Pt, and silicon dioxide were determined from room temperature to 90 °C using Ar, He, Cl@sub 2@, CF@sub 4@, C@sub 2@H@sub 4@, C@sub 4@F@sub 8@, and SF@sub 6@ gases at RF powers from 500 to 1400 W. Measured etch rate for PZT varied from 500 to 2600 Å/min, for Pt from 940 to 1750 Å/min, and for oxide from 50 to 300 Å/min. Experimental results will be presented on selectivity and etched profile of PZT, Pt, and silicon dioxide films at different operating pressures and bias voltages. MEMS (microelectromechanical systems) test structures fabricated using ICP etchers will also be described.

4:40pm **MM-TuA9 Integration of Silicon Anisotropic Wet Etching and BCB Processes***, **N. Ghalichechian**, A. Modafe, R. Ghodssi,* University of Maryland, College Park

We have developed a fabrication process for integration of Benzocyclobutene (BCB) dielectric film and anisotropically etched deep silicon v-grooves in potassium hydroxide (KOH) solution for development of MEMS actuators such as an electrostatic micromotor supported on microball bearings. BCB is a low dielectric constant polymer (k=2.65) with several advantages over silicon dioxide for dielectric insulation such as simple deposition process, low-temperature cure, and low residual stress that are desired in a reliable, efficient electrostatic micromotor. KOH solution is used for fabrication of silicon v-grooves that form a bearing structure to house the micro-balls. We have used gold (Au) film as the etch mask and chromium (Cr) film as the adhesion layer that bonds the Au to the underlying BCB. It was initially observed that the metal films lost adhesion and no longer protected the BCB film during long KOH etching (7 hours in 20 %w solution) process. A fabrication process is developed to improve the adhesion between the BCB and the metal films during the silicon anisotropic bulk micromachining using KOH. This is achieved through several unit process experiments to investigate (a) the effect of cure temperature (210-250 °C), (b) surface treatment of BCB, (c) adhesion improvement at the interface between thin film metals and BCB by applying an adhesion promoter, AP3000, prior to metallization, and (d) the required Cr and Au thickness that results in a robust adhesion to BCB and reliable etch mask for KOH. The optimized experimental results in this work have enabled successful and repeatable fabrication of deep v-grooves (280 µm wide, 220 µm deep) in silicon with BCB (1 µm thick) and Cr/Au (20/500 nm thick) multilayer etch mask. The detailed process parameters and experimental results for this integrative process technology will be presented.

5:00pm **MM-TuA10 Optical Characterization of Poly-Dimethyl Siloxane (PDMS) during Inductively Coupled Plasma Processing for Implementation in a PDMS-based Photonic Crystal****, E.A. Joseph, L.J. Overzet, M.J. Goeckner, **D.S. Park**, M. Tinker, J.B. Lee,* University of Texas - Dallas

Poly-dimethyl siloxane (PDMS) is a silicone elastomer quickly gaining popularity in MEMS and EUV lithography markets. Material etch rates and plasma susceptibility however are not yet fully understood and may significantly effect optical MEMS device performance. In this work, PDMS etch susceptibility is studied in oxygen and CF4 inductively coupled plasma mixtures with in-situ spectroscopic ellipsometry. Initial etch rates as high as 40 µm/hr using a 3:1 mixture of CF4:O2, nearly double that of optimized conventional RIE@footnote 1@ have been obtained, while pure oxygen plasma exposure has been found to increase the refractive index by 7%. A more detailed study of etch rate and dielectric constant dependence on gas flow will be presented along with the implications of using PDMS in a photonic crystal MEMS device. @FootnoteText@ *This work is supported by grants from NSF / DOE, CTS-0079783 & CTS-0078669 and NSF ECS-0296018.@footnote 1@J. Garra, T. Long, J. Currie, Schneider, R. White, and M. Paranjape, J. Vac. Sci. Technol. A 20(3), May/June 2002.

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