The Science of Micro-Electro-Mechanical Systems Topical Conference

Room 610 - Session AS+MI+VM-MoM

Magnetic Recording: Chemical Integration and Tribology

Moderator: R.L. Opila, Bell Labs, Lucent Technologies

8:20am **AS+MI+VM-MoM1 Disk Drive Chemical Integration: Influence of Outgassing on Stiction**, ***D.E. Fowler***, *R.H. Geiss, E. Ghelichkhani,* Maxtor Corporation **INVITED**

Beyond optimizing the magnetic read/write sensor and the magnetic storage media, the successful introduction of a new disk drive product requires the integration of the best electronics and a great mechanical design to surround this magnetic interface. However, all of this effort will be for naught, if the disk drive cannot spin-up because the interface is stuck together or if contamination at the interface causes the sensor-to-media spacing to be a few nanometers greater than the designed fly height. Failure to spin-up can be the result of stiction and, in some cases, a phenomenon called fly stiction. We briefly discuss the distinguishing physical features of stiction induced by the disk lubricant as compared to stiction induced by in-drive outgassing, before focussing on outgassing-induced fly stiction. Various analytical methods have been used to identify the important outgassing sources and materials within the drive. The formation of liquid droplets on the read/write sensor during drive operation has been documented as an important contributor to increased stiction of the sensor-to-media interface following a period of nonoperation. We describe a real time visualization setup which monitors these processes in experimental, but fully functioning disk drives. This offers the opportunity to study the phenomenon and the mechanisms of fly stiction in a realistic drive environment. Results of these visualization experiments are presented. The goal of these studies is to develop a low-stiction interface through the optimization of the chemical integration of the drive. This allows the high-performance magnetic interface to function according to its design.

9:00am **AS+MI+VM-MoM3 The Evolution of the Corrosion Process on Thin-Film Media**, ***J. Ying***, *T. Anoikin, C. Martner,* MMC Technology Inc.

Thin-film hard disks have been exposed to elevated temperature/humidity, and dilute acidic vapor environment. These tests are designed to simulate possible galvanic corrosion, which, for the thin-film media, is characterized by the formation of Co and Ni containing corrosion nodules. The evolution of the corrosion process was elucidated by inducing different degrees of corrosion on the media, and these distinct corrosion stages were characterized morphologically by SEM and chemically by AES compositional analysis. In addition, an XPS chemical state study on the reactivity of Co, Cr, and Ni to ambient and chlorinated environments was conducted. A probable galvanic corrosion mechanism is proposed to understand the chemistry observed during the evolution of the corrosion process. In particular, the effects of ionic contaminants as corrosion accelerators and the role of the Cr underlayer as a corrosion-preventing barrier layer are discussed.

9:20am **AS+MI+VM-MoM4 Tribochemistry of Monodispersed ZDOL with Hydrogenated Carbon Overcoats**, ***C.-Y. Chen***, *W. Fong,* University of California, Berkeley*; D.B. Bogy,* University of California, Berkeley, U.S.

Tribo-chemical studies of the lubricant molecular weight effect on the tribology of the head/disk interface (HDI) were conducted using hydrogenated (CHx) carbon disks coated with ZDOL lubricant. The studies involved drag tests with uncoated and carbon-coated Al2O3-TiC sliders and thermal desorption experiments in an ultra-high vacuum (UHV) tribochamber. The studies showed that the lubricant interaction with the carbon overcoat varies as a function of lubricant molecular weight. The friction coefficient increases as the molecular weight increases. The higher friction is due to the higher viscosity. The friction and catalytic decomposition mechanisms of ZDOL are described. In general, the PFPE polymers are decomposed by chain scission involving the breakage of the backbone bonds to yield free-radical segments. Chain scission can occur by three mechanisms: (1) random degradation, (2) depolymerization, and (3) weak-link degradation. Our studies further support previous observations that catalytic reactions occurred at the endgroup functionals. The lower number of endgroup functionals for ZDOL with higher molecular weight reduces the possibility of the occurrence of catalytic reactions. Moreover, the ZDOL desorbed peak temperatures shifted to lower temperatures with increasing molecular weight in thermal desorption tests. The spreading diffusion coefficient of ZDOL decreases with increasing molecular weight. As the mobility of the lubricant chain decreases, the desorption energy needed to break the lubricants increases, resulting in higher desorption peak temperatures. In addition, the longer chain length of the higher molecular weight ZDOL causes higher degrees of crosslinking. The crosslinking restricts chain mobility and causes an increase in the desorption peak temperatures.

9:40am **AS+MI+VM-MoM5 Thermal Effects on Magnetic Head/Disk Interface Materials**, ***R. Koka***, Read-Rite Corp.*; L. Zhang,* Seagate Technology, Singapore **INVITED**

The materials interacting at the head/disk interface of a rigid disk drive are primarily the disk carbon overcoat, lubricant on the disk, and the head ceramic,Al2O3.TiC. The interface materials can be subjected to high, localized temperatures when the head is flying or sliding on the disk or when wear debris is trapped in the interface. The head or disk by itself can be exposed to high temperatures during the manufacturing process. This presentation addresses some of the changes that occur in the interface materials when they are individually subjected to high temperatures. Raman spectroscopy of thermally annealed disks will be presented to show that the carbon overcoat tends to become slightly graphitic. At 350C in air, the overcoat oxidizes rapidly and completely disappears. The widely used PFPE lubricants (ZDOL & AM) used on disks, degrade at high temperatures (~350C). In the presence of Lewis acids, the degradation process occurs at lower temperatures (~200C) and the rate of degradation is very high. The products of thermal degradation are different for the two lubricants because of the functional end groups. With respect to tribology, a head made of a passive ceramic such as SiC tends to perform relatively better than a material such as Al2O3.TiC, which is known to be an aggressive catalyst for lube degradation. Annealing of the Al2O3.TiC head ceramic shows that around 350C, carbon diffuses from the TiC grains and titanium oxides are formed. The diffused carbon is amorphous with a mixture of sp2 and sp3 bonds and it becomes nanocrystalline graphite above 600C. Thin, diamond-like, carbon coatings (60A thick) on the surface of the head effectively protect the Al2O3.TiC from oxidation and carbon diffusion at temperatures below 500C. A few examples of disk wear and smear formations on heads and disks will be presented. Some similarities between the Raman spectra of smears on heads and annealed disk overcoats and degraded lubricant will be discussed.

10:20am **AS+MI+VM-MoM7 The Process Induced Changes on the Co-alloy Films and the Tribological Effects on Magnetic Recording Heads**, ***Y.S. Chaug***, *R. Adams,* Storage Technology Corporation

The ferromagnetic alloys of Co-metal systems are soft magnetic materials having large saturation magnetization and low coercive force. Sputter deposited Co@sub 1-x@(Zr,Ta)@sub x@ (0.05<x<0.16) amorphous films have been used as magnetic pole material in magnetic inductive heads for its zero magnetostriction. In the wafer process, the Co@sub 1-x@(Zr,Ta)@sub x@(CZT) films were patterned through the photolithography process and then treated with an oxygen plasma for cleaning. The surface changes on the processed CZT surface were studied using x-ray photoelectron spectroscopy. The migration of Co ions to the CZT surface was found after the oxygen plasma treatment. Atomic force microscope, scanning electron microscope and Nano-Triboscope were used to examine the changes of the Co rich CZT surface in a high humid environment. The process induced changes on the CZT surface which impacted the ABS (air bearing surface) lapping process in manufacturing the magnetic inductive heads. The tribology of the magnetic recording heads using CZT as magnetic pole will be discussed.

10:40am **AS+MI+VM-MoM8 Study of Tribochemical Processes at the Head-disk Interface Using Photoemission Electron Microscopy**, ***S. Anders***, *A. Scholl, F. Nolting,* Lawrence Berkeley National Laboratory*; W. Fong, C.-Y. Chen,* University of California, Berkeley*; D.B. Bogy,* University of California, Berkeley, U.S.*; C.S. Bhatia,* SSD/IBM*; J. Stohr,* IBM Almaden Research Center

Photoemission electron microscopy (PEEM) has been applied to study the tribochemical processes at the head-disk interface of magnetic storage devices. High resolution PEEM imaging is based on several contrast mechanisms (topographical, elemental, chemical, and various forms of polarization contrast) which makes it a unique tool for the study of tribochemical processes. We have studied surfaces of hard disks and sliders after various kinds of wear tests performed in ambient atmosphere and UHV. It was observed that the disk surface in the wear tracks is chemically modified if visible wear occurred and if a lubricant was present. In the case of unlubricated disks no chemical modifications were observed but a reduction in the hard carbon overcoat thickness. The chemical modifications consist of lubricant oxidation and fluorine removal. The

lubricant oxidation and fluorine removal is enhanced with enhanced wear. It was found that degraded lubricant is transferred to the sliders and accumulated in scratches of the slider surfaces. The hard carbon overcoat on sliders was found to be reduced in thickness after the wear tests, but not chemically altered.

11:00am **AS+MI+VM-MoM9 Tribo-Chemistry of the Head-Disk Interface in Hard Disk Drives**, ***D.B. Bogy***, University of California, Berkeley, U.S.; *C.S. Bhatia,* IBM SSD; *C.-Y. Chen, W. Fong,* University of California, Berkeley **INVITED**

Tribo-chemical studies of the lubricant thickness effect on the tribology of the head/disk interface (HDI) were conducted using hydrogenated (CHx) carbon disk samples coated with perfluoropolyether ZDOL lubricant. The studies involved drag tests with uncoated and carbon-coated Al@sub 2@O@sub 3@-TiC sliders and thermal desorption experiments in an ultra-high vacuum (UHV) tribochamber. The studies showed that the lubricant interaction with the carbon overcoat varies as a function of lubricant thickness. Wear durability improves considerably for thicknesses greater than a monolayer. However, in the sub-monolayer thickness regime, the adhesion of the lubricant to the carbon overcoat is much stronger, as indicated by the fact that a much higher temperature is required to desorb the lubricant. When the lubricant thickness is around or above a monolayer, cohesion among the lubricant molecules plays a greater role and a much lower temperature is needed for lubricant desorption. In addition, we observed that hydrogen evolution from CHx overcoat initiates lubricant catalytic decomposition, forming CF3 and C2F5. The generation of HF during the thermal desorption experiments provides the formation mechanism of HF, which is the necessary component for catalytic reaction.

11:40am **AS+MI+VM-MoM11 Phase Transitions in Two-dimensional Ferroelectric Films**, ***C.N. Borca***, *J. Choi, S. Adenwalla, P.A. Dowben, M. Poulsen,* University of Nebraska, Lincoln; *J.L. Robertson,* Oak Ridge National Laboratory; *V.M. Fridkin, S.P. Palto, N. Petukhova, S.G. Yudin,* Russian Academy of Science; *S. Ducharme,* University of Nebraska, Lincoln

We studied ferroelctric copolymer films of vinylidene fluor ide with trifluoroethylene, P(VDF-TrFE) 70:30. The films exibit ferroelectric switching properties and can be used in a variety of piezoelectric devices. In addition to the first order ferroelectric to paraelectric bulk transition at 80 degrees C, we report two other phase transitions. One appears at 20 degrees C and is related entirely to a surface ferroelectric transition.@footnote 1@ The third transition around 150 degrees K is due to a stiffening of the lattice and a change in the bulk electronic structure. For P(VDF-TrFE), there is a negligible density of states at the Fermi level making this phonon related transition very unusual. This last transition was observed using neutron diffraction, @footnote 2@ X-ray diffraction, photoemission spectroscopy and EELS. The effective Debye temperature decreases from a value of about 250 K to 50 K with increasing temperature across the 150 K lattice stiffening transition. @FootnoteText@ @footnote 1@J. Choi, P.A. Dowben, S. Pebley, A.V. Bune, S. Ducharme, V.M. Fridkin, S.P. Palto, N. Petukhova, Phys. Rev. Lett. 80, 1328 (1998) @footnote 2@C.N. Borca, J. Choi, S. Adenwalla, Stephen Ducharme, P.A. Dowben, Lee Robertson, V.M. Fridkin, S.P. Palto, and N. Petukhova, Appl. Phys. Lett. 74, 347 (1999).

Thin Films Division
Room 615 - Session TF+MM-WeM

Thin Films in MEMS and MOEMS

Moderator: S. Patton, Air Force Research Laboratory

8:20am **TF+MM-WeM1 Detection of Photons Using Thin Films in Semiconductor MEMS**, ***P.G. Datskos,*** *S. Rajic,* Oak Ridge National Laboratory*; I. Datskou,* Environmental Engineering Group, Inc.

We report on a new method for detecting photons using the stress caused by photoelectrons emitted from a thin metal film surface in contact with a semiconductor microstructure which forms a Schottky barrier. As photoelectrons diffuse from the metal film into the microstructure they produce an electronic stress. The photon detection results from the measurement of the photo-induced bending of the microstructure. Internal photoemission has been used in the past to detect photons, however, in those cases the detection was accomplished by measuring the current due to photoelectrons and not due to electronic stress. Small changes in position (displacement) of microstructures are routinely measured in atomic force microscopy (AFM) where atomic imaging of surfaces relies on the measurement of small changes (< 10@sup -9@ m) in the bending of microcantilevers. In this work we studied the photon response of Si microcantilevers coated with a thin film of Pt. The Si microcantilevers were 500 nm thick and had a 30 nm layer of Pt. Photons with sufficient energies produce electrons from the platinum-silicon interface which diffuse into the Si and produce an electronic stress. Since the excess charge carriers cause the Si microcantilever to contract in length but not the Pt layer, the bimaterial microcantilever bends. In our present studies we used the optical detection technique to measure the photometric response of Pt-Si microcantilevers as a function of photon energy. The charge carriers responsible for the photo-induced stress in Si, were produced via internal photoemission using a 1550 nm wavelength diode laser.

8:40am **TF+MM-WeM2 Sputtered Coatings for Microfluidic Applications**, ***D.W. Matson,*** *P.M. Martin, W.D. Bennett, J.W. Johnston, D.C. Stewart, C.C. Bonham,* Pacific Northwest National Laboratory

Magnetron sputter-deposited features and coatings are finding a broad range of uses in microfluidic devices being developed at the Pacific Northwest National Laboratory (PNNL). Such features have routinely been incorporated into multi-layer laminated microfluidic components where specific functionality is required and other methods for producing these features have been deemed unacceptable. Applications include electrochemical sensors, heaters and temperature probes, electrical leads and insulation layers, and chemical modification of surfaces. Small features, such as those required for the production of microsensor electrodes or miniature resistive heaters on microfluidic chips, were patterned using standard lithographic methods or with masks produced by laser micromachining processes. Use of the coating technology and its application in specific microfluidic devices, including a groundwater sensor, a piezoelectrially actuated airflow regulator, and a microchannel flow diagnostic device, will be discussed.

9:00am **TF+MM-WeM3 A Novel Thin-Film Proton Exchange Membrane Fuel Cell for Microscale Energy Conversion**, ***J.D. Morse,*** *A.F. Jankowski, J.P. Hayes, R.T. Graff,* Lawrence Livermore National Laboratory

A novel approach for the fabrication and assembly of a proton exchange membrane (PEM) fuel cell system enables effective scaling of the fuel delivery, manifold , and cell stack components for applications in miniature and microscale energy conversion. Electrode materials for PEM fuel cells are developed using sputter deposition techniques. A thin film anode is formed through the deposition of nickel, followed by the deposition of a platinum catalyst layer. A proton conducting membrane electrolyte is formed over the catalyst using spin cast techniques. Finally, a thin film cathode is formed that incorporates a thin platinum layer, followed by a layer of silver. Scaling towards miniaturization is accomplished by utilizing novel micromachining approaches. Manifold channels and a fuel delivery system are formed within the substrate that the cell stack is fabricated on thereby circumventing the need for bulky manifold components that are not directly scalable. Methods to synthesize a base electrode layer to a thin-film PEM fuel cell from the electrolyte and a conductive material are developed using photolithographic patterning and physical vapor deposition. The microstructure and morphology desired for the anode layer should facilitate generation of a maximum current density from the fuel cell. For these purposes, the parameters of the deposition process and post-deposition patterning are developed to optimize porosity in the anode layer. The fuel cell microstructure is examined using scanning electron microscopy and the power ouput generated is characterized through current-voltage measurement. This work was performed under the auspices of the United States Department of Energy by Lawrence Livermore National Laboratory under contract #W-7405-Eng-48.

9:20am **TF+MM-WeM4 Thin Films in MEMS and MOEMS**, ***W.D. Cowan,*** Air Force Research Laboratory **INVITED**

Micro-Electro-Mechanical Systems (MEMS) and Micro-Optical-Electro-Mechanical Systems (MOEMS) employ batch fabrication processes to construct miniature devices with macroscopic functionality. Surface micromachined MEMS structures are manufactured by the deposition and patterning of thin films. In marked contrast with conventional fabrication processes (and bulk micromachining), the thin film materials used in surface micromachined structures are formed as the device is processed. In general, the material properties of thin films are not controlled during deposition, and are only measured after processing is completed. Characterization methods include wafer curvature measurements and a variety of test structures. None of the thin film characterization techniques currently employed is entirely satisfactory and all methods rely on process repeatability to be useful. The ultimate performance of many MEMS and MOEMS depends directly on the materials properties of the thin films employed. Processing variations induce variations in materials properties that directly impact device performance. For MOEMS, residual material stresses can cause curvature of nominally flat reflecting surfaces that degrades optical performance. Recent work in which MEMS foundry processes were used to fabricate low-cost deformable mirrors (MEM-DMs) for adaptive optics illustrates the impact of residual material stress on system level optical performance. Residual material stress can be exploited in other MEMS devices to produce unique structures. More precise monitoring and control of film stress during deposition remains as a challenge for MEMS and MOEMS.

10:00am **TF+MM-WeM6 Residual Stresses in MEMS Structures**, ***B.S. Majumdar,*** UES, Inc.*; W.D. Cowan,* Air Force Research Laboratories*; S. Rogers,* AFIT*; N.J. Pagano,* Air Force Research Laboratories

Residual stresses impose major restrictions on the performance of MEMS devices. Although different techniques have been developed to measure such stresses, they suffer from a number of limitations. We have focused our attention on square and circular micro-mirrors that are supported by electrically activated arms. Permanent curvature in such mirrors arise from thermal and process-generated residual stresses, and they seriously impair mirror performance. In this work, the residual stresses were estimated from curvature measurements on different sized beams using an interferometric technique, complemented by rigorous elastic analysis of composite beams. It is notable that typical analyses is based on Stoney's equation, which is not believed to be valid for the thin MEMS structures. The composite beams consisted of different grades of poly-silicon with and without gold coating, and the measurements and analysis showed consistent results for the different beams and mirrors. In an effort to de-couple the thermal and process component of the residual stresses, curvature measurements were made at different temperatures. The results and analysis technique will be presented in detail, and possible methods to reduce the residual stresses will be discussed.

10:40am **TF+MM-WeM8 Investigation and Modeling of Electrical Resistance in Polysilicon Thermal Actuators**, ***J.T. Butler,*** *W.D. Cowan,* Air Force Research Laboratory

This paper reports on investigation and modeling of the electrical resistance of micromachined polysilicon thermal actuators. The availability of models compatible with commonly used circuit simulators such as SPICE are extremely useful for design of integrated microsystems which include thermal actuators. The development of a model for thermal actuators necessitated an analysis of the electrical resistance characteristics of the MEMS fabrication process in order to provide an understanding of a key material property. The thermal actuators investigated in this research were fabricated through the DARPA-sponsored Multi-User MEMS Processes (MUMPs). Hence, a TSUPREM model of the MUMPs fabrication process was created to generate polysilicon resistivity parameters which were then fed into the electrothermal SPICE model. Two types of thermally actuated devices were modeled: a lateral thermal actuator and a thermally actuated piston micromirror. The SPICE model exhibits very close agreement with the measured performance of the polysilicon thermal actuators. The MUMPs process used to fabricate the thermal actuators has three structural layers of polysilicon. The resistivity of each of the MUMPs

polysilicon layers varies due to differences in fabrication. Moreover, our resistance measurements of test structures and actuators showed that the resistivity of devices formed from the various MUMPs polysilicon layers also varies based on structure linewidth. A TSUPREM fabrication model of the MUMPs process was generated which validated the empirical resistance measurements and the dependence of resistivity on linewidth. The TSUPREM simulation revealed that the diffusion of phosphorus dopant during the anneal cycles in the MUMPs fabrication process were largely responsible for the variations in resistivity due to linewidth. For small (< 10 (m) linewidth structures, the presence or absence of lateral diffusion of dopant through the sidewall can significantly alter the electrical resistance. The resistivity dependence on linewidth is significant for our thermal actuators because they are designed with elements having linewidths varying from 2 (m to greater than 20 (m. The electrothermal SPICE model augmented with the TSUPREM resistivity data accurately predicted the I-V performance of both the lateral thermal actuator and the thermal piston micromirror. The use of SPICE allows simulation of both the MEMS device and control electronics in the same analysis package and enables the designer to gain insight into the expected performance of the microsystem prior to fabrication. On-going work includes investigation of adding thermal mechanical modeling to our simulation.

The Science of Micro-Electro-Mechanical Systems Topical Conference

Room 620 - Session MM-WeA

Micro-Science and Tribology

Moderator: C. Zorman, Case Western University

2:00pm **MM-WeA1 Micro-Science and Tribology**, ***L. Lin,*** The University of Michigan **INVITED**

Microelectromechanical Systems (MEMS) have emerged as an interdisciplinary field in recent years and encompassed a wide range of scientific and engineering areas such as electrical engineering, mechanical engineering, material sciences, physics and chemistry. Tribological issues dealing with adhesion, abrasion, corrosion and erosion are generally encountered in macroscopic machinery and are inevitable problems for micro-science. The technological and economical impacts of tribological issues in MEMS demand fundamental understanding and characterization in material development, design, processing and testing of microstructures. Micro devices that are fabricated by IC (Integrated Circuit) processes represent very different surface features than those macro structures fabricated by conventional mechanical manufacturing processes. It is important to study the micro-science of tribology and investigate the tribological effects in the microscale for optimal design and processing of MEMS. This talk will present several important tribological effects, including surface roughness of the microstructures to the nucleation of micro thermal bubbles, to the mechanical properties and to the optical properties of microstructures. The causes and solutions of the surface force induced sticking failures in MEMS will be discussed. A review of MEMS micromachining processes describing key manufacturing steps is followed by practical engineering examples. Future research directions will be proposed in the conclusion.

2:40pm **MM-WeA3 Deposition, Characterization and Degradation of Vacuum-deposited Fluorinated Alkylsiloxane Films**, ***T.M. Mayer,*** *M.P. de Boer, N.D. Shinn, T.A. Michalske,* Sandia National Laboratories

We deposit monolayer films of fluorinated alkylsiloxanes by a chemical vapor deposition process using C@sub 8@F@sub 13@H@sub 4@SiCl@sub 3@ and H@sub 2@O. Films are formed under well controlled conditions of reactant exposure and temperature, from 25 - 300@super o@ C. Using in-situ ellipsometry and quartz crystal microbalance techniques, we show that film thickness is self limiting at approximately one monolayer due to coverage dependent adsorption of precursors. Adhesion measurements of micromechanical structures coated with these films show typical adhesion energies of ~20 μJ/m@super 2@ at low humidity conditions. Exposure to high humidity environments for long periods results in degradation of the films and stronger adhesion. We postulate that this degradation is related to defects in the films, which are susceptible to hydrolysis by adsorbed water. We examine this postulate by measuring adhesion for varying film coverage, and by examining the morphology of freshly deposited and aged films by atomic force microscopy. Friction measurements correlated to film structure and history are examined as well in micromechanical test devices using structures coated with these films.

3:00pm **MM-WeA4 Vapor-Phase Lubricants: Nanometer-scale Mechanisms and Applications to Sub-micron Machinery**, ***M. Abdelmaksoud,*** *B. Borovsky, J. Krim,* North Carolina State University

The concept of lubricating high temperature bearing surfaces with organic vapors which react with a surface to form a solid lubricating film has existed for at least forty years, with substantial efforts beginning in the 1980's and continuing to the present day. While vapor-phase lubricants have primarily been studied within the context of macroscopic system performance, they may well prove to be of critical importance to tribological performance in sub-micron mechanical systems as well: The vapor phase may ultimately prove to be the most effective, if not only, means to deliver and/or replenish a lubricant on account of the submicron scale of the device itself. In order to investigate the viability of vapor-phase lubrication for MEMS applications, we have studied the molecular scale properties of a number of known or proposed vapor-phase lubricants in controlled environments and well-defined contact geometries.A first study involves Auger Spectroscopy and Quartz Crystal Microweighing investigations of the known lubricant TBPP as it reacts with an iron film surface prepared in ultra-high vacuum conditions. Confirming prior conjecture, we observe that exposure of iron to TBPP vapors results in a rigidly adhering film with a graphitic carbon component which presumably is the lubricating component. With the intent of modelling actual MEMS contacts, we have also constructed a simple nanomechanical system consisting of a Scanning Tunneling Microscope tip dragging on the surface of a Quartz Crystal Microbalance electrode. This system allows us to monitor lubricant performance in realistic sliding conditions. Of the systems which we have observed to date, those films which are associated with the greatest decreases in friction have also been the quickest to wear away due to the rubbing action of the STM/QCM combination. Work is now in progress to study the effect of these vapor-phase lubricants on actual MEMS devices, namely comb motors.

3:20pm **MM-WeA5 Adhesion Performance of Silane Coupling Agents at High Humidity Levels**, ***M.P. de Boer,*** *T.M. Mayer, T.A. Michalske, R.W. Carpick,* Sandia National Laboratories*; R. Maboudian, U. Srinivasan,* University of California, Berkeley

We have measured the effect of humidity on autoadhesion of polycrystalline silicon cantilever beams fabricated by surface micromachining, and coated with silane coupling agents. To make the measurements, we designed and constructed an environmental microprobing station with interferometric capability, and automated the system to enable measurement of beam deflections in-situ. We quantified adhesion by applying a fracture mechanics equilibrium to each adhered beam. For both ODTS (C@sub 18@H@sub 37@SiCl@sub 3@) and FDTS (C@sub 8@F@sub 17@C@sub 2@H@sub 4@SiCl@sub 3@) coatings, the effect of relative humidity (RH) is negligible for RH up to approximately 80%. For ODTS coatings at 99% RH after a 40 hour exposure, adhesion increases only moderately by a factor of two. For FDTS coatings at 90% RH, adhesion increases dramatically by a factor of 100 after seven hours, with further subsequent increases at higher RH values. This is a surprising result, considering that FDTS has a higher contact angle with water than does ODTS, and exhibits lower adhesion at low RH. We believe that defect formation is responsible for the adhesion increase. To support this assertion, we conducted water absorption experiments and obtained atomic force microscopy images revealing agglomerated coupling agent on films exposed to high RH. ODTS is less susceptible to this mechanism than FDTS because of its greater chain length and smaller chain diameter. Our results contrast with experiments on fatty acid monolayers using the surface force apparatus, where uniform swelling of the film is responsible for a monotonic adhesion increase with RH.

3:40pm **MM-WeA6 Adhesion Properties of Gold-on-Gold Microswitch Contacts**, ***S. Majumder,*** *N.E. McGruer, G.G. Adams, P.M. Zavracky, R.H. Morrison,* Northeastern University*; J. Krim,* North Carolina State University

Electrostatically actuated microswitches have been developed at Northeastern University. As part of this effort, gold-on-gold microswitch contacts have been studied on the basis of electrical measurements, surface analysis, and an analytical model of the contacts.@footnote 1@ Measurements show that the turn-off voltage of the switch is often substantially smaller than the turn-on voltage, an effect which is not predicted by an electromechanical model of the actuation mechanism. Also, contact stiction is a dominant mode of eventual switch failure. Motivated by these observations, we extend our study of contacts to include adhesive surface forces at the contact interface. We consider the applicability of the JKR and DMT surface force models.@footnote 2@ to our problem. We examine the validity of these models through various measurements. Under typical operating conditions, the contact force is approximately 40 μN, the spring force which returns the switch to the off position is 150 μN, and the adhesion force (minimum spring force required to turn off the switch) usually ranges from 10-50 μN for a major portion of the switch lifetime (10@super 4@ - 10@super 6@ switching cycles). Failure by stiction is preceded by a gradual increase in the adhesion force. The adhesion force has a strong (inverse) correlation with the contact resistance, and some correlation with the maximum applied contact force during the on-cycle. Other results that are compared with the model include the variation of contact resistance with contact force during loading and unloading, the contact resistance when the switch just turns on and off, and the effect of loading history. @FootnoteText@ @footnote 1@ S. Majumder, N.E. McGruer, P.M. Zavracky, G. G. Adams, R. H. Morrison, J. Krim, Transducers '97, Chicago, IL (1997). @footnote 2@ M. D. Pashley, J. B. Pethica, D. Tabor, Wear, vol. 100, pp. 7-31, 1984. .

4:00pm **MM-WeA7 Environmental Effects on the Tribological Behavior of Silane-Treated Micromachines@footnote 1@**, ***M.T. Dugger,*** *J.A. Ohlhausen, G.A. Poulter,* Sandia National Laboratories

Reproducible performance of silicon surface micromachined devices having contacting surfaces in relative motion requires that contact surfaces

maintain uniform friction coefficient over the useful life of the device. High yield fabrication of such structures also requires that the moving surfaces are physically free from other surfaces after the final manufacturing step. Several methods are available to produce hydrophobic surfaces on silica at the conclusion of manufacturing, so that capillary forces do not pull structural elements into contact. These may also favorably affect the friction coefficient and wear characteristics of the treated surfaces. However, these chemical surface terminations may be degraded by wear, and the degradation may be influenced by reactive species present in the gas phase. Polycrystalline silicon test structures have been used to determine the friction coefficient and durability of silane-based surface treatments in controlled environments. Water vapor present in the environment leads to changes in friction coefficient and device failure at fewer operating cycles than when water vapor is absent. Surface analysis and mechanistic aspects of interaction of the silane-treated surface with water vapor will be discussed. @FootnoteText@ @footnote 1@ This work was supported by the United States Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

4:20pm **MM-WeA8 Selective Organophosphonate Chemical Sensors Using Self-Assembled Composite Monolayers and Adsorption-Induced Stresses in MEMS Devices**, *P.G. Datskos,* ***H.M. Meyer,*** Oak Ridge National Laboratory*; D. Karst,* Virginia Tech*; M.J. Sepaniak,* University of Tennessee

Recently there has been an increasing demand to perform real-time in-situ chemical detection of hazardous materials, contraband chemicals, and explosive chemicals. Currently, real-time chemical detection requires rather large analytical instrumentation that are expensive and complicated to use. The advent of inexpensive mass produced MEMS (micro-electro-mechanical systems) devices opens-up new possibilities for chemical detection. For example, microcantilevers were found to respond to chemical stimuli by undergoing changes in their bending and resonance frequency even when a small number of molecules adsorb on their surface. We describe a novel organophosphonate chemical sensor that is based on adsorption-induced stresses in MEMS (micro-electro-mechanical systems) and self-assembled monolayers. The MEMS microcantilever chemical sensor was found to exhibit high sensitivity, reversibility and chemical selectivity. Target molecules adsorbed on the surface of a microcantilever induce a differential surface stress causing changes in both the resonance frequency of the microcantilever and its bending. Measurable changes in the microcantilever bending always occur before any measurable resonance frequency shifts. Monitoring the bending of the microcantilever as molecules adsorb on its surface provides an extremely sensitive means of chemical sensing. In addition, monitoring of resonance frequency changes provides another sensing mechanism similar to the manner SAW and QCM devices operate. The chemical selectivity and reversibility of the present chemical sensor is based on the action of composite self-assembled monolayers. We will report on the response of microcantilevers with composite self-assembled monolayers to DIMP and DMMP. Our results show that such microcantilever chemical sensors exhibit rapid response times and high selectivity to organophosphonate compounds.

4:40pm **MM-WeA9 Nanofabrication and Electrostatic Operation of Single-crystal Silicon Paddle Oscillators**, *D.W. Carr, S. Evoy,* ***L. Sekaric,*** *A. Olkhovets, J.M. Parpia, H.G. Craighead,* Cornell University

Nanoelectromechanical systems (NEMS) are of interest from both scientific and technological standpoints. Such structures are being considered for use as sensors, force gauges and for various optomechanical and biomedical applications. Small resonant structures also open avenues for mesoscopic studies of the mechanical properties of materials. We have recently reported the fabrication and excitation of single wires with resonant frequencies as high as 380 MHz. Here we report the fabrication and characterization of paddle oscillators with nanometer-scale supporting rods. The devices are electrostatically driven and are detected at room temperature using an optical interferometric technique. The devices show two resonances in the f =1-10 MHz range. We have measured the frequency of both resonances for a series of devices of varying paddle length, d. A fit of data to a f = Kd^b power law reveals experimental power coefficients of b1=-0.5Â±0.1 and b2=-1.6Â±0.15 for the two resonances. These coefficients agree with the values expected for translational and torsional modes of motion, respectively. Our model of the torsional mode suggests that the external drive induces an angular dependent electrostatic torque, resulting in a modulation of the torsional constant. This results in a shift of the resonant frequency under the application of a DC bias. Dependence of this shift on the bias allows us to extract a mechanical torsional constant of tau= 4.21Â±0.04 x 10-12 N.m. This modulation also results in parametric amplification effects that are under investigation. The translational motion shows non-linear behavior at low driving RF amplitudes. A model based on the mechanical stretching of the beams predicts the onset of non-linearity at such amplitudes. Finally, we will discuss the effects of material and surface properties on the dissipative processes in these structures. We are also looking at alternative geometries and potential chemical sensing applications.

5:00pm **MM-WeA10 MEMS-Based Force Detected Nuclear Magnetic Resonance Spectrometer**, ***T. George,*** *W. Tang, A. Chang-Chien, D.W. Elliott,* Jet Propulsion Laboratory*; L. Madsen, G. Leskowitz, D. Weitekamp,* California Institute of Technology

A novel nuclear magnetic resonance (NMR) spectrometer was recently demonstrated. In contrast to conventional NMR spectroscopy, which involves the detection of RF absorption, the force-detection technique works on the principle of using the RF to resonantly invert the magnetization of the sample of interest. The magnetization inversion is carried out at the mechanical resonance frequency of a microfabricated harmonic oscillator consisting of a silicon "diving board" on which a sensor magnet is mounted. The motion of the oscillator in response to the inversion of the sample magnetization is detected using fiber-optic interferometry. A two pronged approach was undertaken to develop the MEMS-based instrument. Microfabrication techniques including deep reactive etching of silicon and micro-electroplating of Fe-Ni alloys are being developed for the 2 mm diameter MEMS instrument. In parallel, a 25 mm diameter, conventionally machined magnet array mounted on a microfabricated silicon "diving board" has been used successfully to demonstrate the proof-of-concept. NMR spectroscopy has been conducted using this device, on millimeter-sized water droplets. Spin-echo experiments have also been undertaken to reduce the linewidth of the NMR peaks to below <1 Hz. The results of these experiments and the fabrication process will be described in detail. Applications of FDNMR spectroscopy in planetary exploration will also be discussed.

The Science of Micro-Electro-Mechanical Systems Topical Conference

Room 620 - Session MM+MI-ThM

Processing and Integration Technology

Moderator: L.M. Miller, Jet Propulsion Laboratory

9:00am **MM+MI-ThM3 Magnetic Micromachining Technology: From Materials to Components to Actuators**, ***M.G. Allen***, Georgia Institute of Technology **INVITED**

The fabrication of micromachined structures based on magnetic elements requires the development of both magnetically soft and hard materials, as well as suitable processes that allow the incorporation of these materials into microelectromechanial systems (MEMS). This presentation summarizes approaches to materials and fabrication techniques for magnetic MEMS, and illustrates their use through several examples, including: flux concentrators to improve the sensitivity of magnetotransistors; integrated inductive components for electronic packages; and fully-integrated, magnetically-actuated microrelays.

10:20am **MM+MI-ThM7 Fabrication and Characterization of Polycrystalline Silicon Thin Films with Hydrofluoric Acid Permeability for Sacrificial Etching of Underlying Oxide Layers**, ***Y. Kageyama***, *T. Tsuchiya, H. Funabashi, J. Sakata,* Toyota Central R&D Labs., Inc., Japan

Polycrystalline silicon (poly-Si) thin films with permeability to a concentrated hydrofluoric acid solution were fabricated for use in in-situ vacuum encapsulation of micro sensor devices on silicon wafers, and porous microstructures of the films related to the permeability were elucidated. A partial cavitation of grain boundaries, which was induced by heavy doping of phosphorus and consequent segregation of soluble precipitates, was designed for passage of fluid which resolves underlying borophosphosilicate glass (BPSG) or non-doped silica glass (NSG) layer. Poly-Si films of 0.1µm in thickness were made by solid phase crystallization of amorphous films deposited by low-pressure chemical vapor deposition, and were converted to be permeable by doping. Three types of the doping methods were tried, and only a phosphorus oxichloride decomposition method proved to be effective to obtain permeability. The permeability was evaluated by measuring selective removal rates of underlying sacrificial oxide layers, and lateral BPSG removal of more than 50µm was observed within 90 sec at a room temperature through the permeable poly-Si thin films. The removal rates of BPSG layers were about ten times faster than those of NSG layers, which can be attributed to phosphorus concentration in oxide, and were dependent on post-annealing temperatures, whereas those of NSG layers did not depend on the annealing temperatures. The microstructures of these permeable poly-Si thin films were first observed by secondary electron microscope and field emission secondary electron microscope, which revealed submicron pores between silicon grains that acted as the fluid paths.

10:40am **MM+MI-ThM8 A New Chemistry for Rapid Etching of SiO@sub2@**, ***C.I.H. Ashby***, *C.M. Matzke, L. Griego,* Sandia National Laboratories

Plasma etching of SiO@sub2@ has traditionally been achieved using a fluorocarbon-based plasma. Very fast SiO@sub2@ etch rates (> 1 µm/min) are obtained using high-density plasmas and CH@subx@F@suby@ source gases. Although these plasmas provide fast preferential etching of SiO@sub2@ vs. Si by controlled deposition of a polymer, that same polymer deposition makes CH@subx@F@suby@ processes unsuitable for applications where the surface chemical properties of the SiO@sub2@ are important. Fabrication of deep trenches in fused SiO@sub2@ without chemical alteration of the SiO@sub2@ surface by a fluoropolymer deposit is essential for applications such as electrophoretic and electro-osmotic separations using microfabricated channels ("chemlab on a chip"). Rapid (0.4 µm/min) etching of fused silica has been achieved without the use of polymerizing fluorocarbon gases by the addition of N@sub2@ to SF@sub6@/Ar mixtures in an electron-cyclotron-resonance (ECR) reactor. Addition of N@sub2@ to SF@sub6@ increases the etch rate of SiO@sub2@ by up to 30%. After deep (10 µm) trench etching, the smoothness of the etched surface is comparable to that of unetched SiO@sub2@. Nitrogen might play two roles in enhancing SiO@sub2@ etching: 1) increasing the F atom concentration and/or 2) facilitating the etching of the SiO@sub2@ matrix through the formation of volatile NO@subx@ products. Optical emission studies using Ar actinometry suggest the second mechanism dominates under our plasma conditions. Process characteristics under a variety of plasma conditions will be presented. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

11:00am **MM+MI-ThM9 Residual Stress Characterization of Thick PECVD Oxide Films for MEMS Applications**, ***R. Ghodssi***, *X. Zhang, K.-S. Chen, K.A. Lohner, M. Spearing, M.A. Schmidt,* Massachusetts Institute of Technology

Vapor deposited films are of vital importance in many sensors and actuators where they are used to form electrical or mechanical elements. In order to achieve higher electrical and mechanical power levels, thicker films are often desired. However, the deleterious effects of residual stress tend to increase with film thickness. In particular, excessive wafer bow and even cracking may prohibit integration within a micro-device. This paper presents residual stress characterization for PECVD Novellus@super TM@ oxide films with thicknesses in the range of 10 - 40 µm. These films are deposited at 400°C and densified at 1100°C in a nitrogen environment. Wafer curvature measurements were performed to investigate the residual stress in the thick PECVD oxide films as a function of temperature. These results show that the residual stress in thick PECVD oxide films is a combination of both thermal expansion mismatch stress and an intrinsic stress due to the deposition process and resulting microstructure. Furthermore, the densification step plays an important role in determining the residual stress state. For instance, a 10 µm thick PECVD oxide film exhibits a wafer bow of 50 µm and 250 µm before and after densification, respectively. Additional high temperature experiments indicated that cracks formed at temperatures between deposition and densification. The tendency to form cracks is a strong function of film thickness. For films thicker than 15 µm, cracks formed in the film at temperature below 1100°C. Laminated plate theory has been applied to extract residual stress data for the curvature measurements. This data is then correlated with the deposition and densification conditions to guide process development so as to reduce wafer curvature and to eliminate cracking.

11:20am **MM+MI-ThM10 Process and Fabrication of a Thin Film PZT Pressure Sensor**, ***E. Zakar***, *M. Dubey, B. Piekarski, J. Conrad, R. Piekarz, R. Widuta,* Army Research Lab

Piezoelectric crystals or ceramics are very attractive for static and dynamic pressure sensors. One of the very promising piezoelectric materials is PZT (Lead Zirconate Titinate - 52/48). MEMS technology was applied to fabricate several static PZT pressure sensors and capacitance method was used to characterize it. Sol-gel derived PZT thin films (250 - 500 nm) were deposited on platinized (SiO@sub 2@- 1000/ Ti - 20/ Pt - 170 nm) Si substrates. Top Pt electrode was sputtered deposited on PZT films and was patterned using ion milling. The PZT films were etched using Reactive Ion Etching (RIE) and ion milling. Comparative studies (etched surface, sidewalls and electrical properties) of ion milling and RIE of PZT and oxide were also completed. The RI etch rate of PZT was studied using different electrode shield (graphite, alumina, ardel) materials with power (100 to 500 W) and pressure of HC@sub 2@ClF@sub 4@ gas plasma. The measured RI etch rate of PZT varied from 10-100 nm/min. The ion-milling rate of Pt was 33nm/min, PZT-23nm/min and Oxide-31nm/min. A unique technique of soft and hard bake of photo resists along with change in incidence angles of ion beam were used to eliminate fencing problem during ion milling. Desired slope of the etched walls was also produced using above technique. The etched surface and side walls were smooth and clean up to 2µm feature size. Four level photo-mask process was used to fabricate the pressure sensors. A low stress PECVD oxide film was deposited (at 200°C) to isolate the top and bottom electrodes. The Pt electrodes further bonded with Ti/Au leads which were patterned using wet etching (KOH + I@sub 2@). Several pressure sensors with different dimensions (300x300 and 200x200 µm@super 2@) were fabricated. The average values of measured capacitance, 1023 and 453 pF, are in excellent agreement with calculated values.

11:40am **MM+MI-ThM11 Microfabricated Low-Power Broad-Band Light Source Utilizing Tungsten Filaments**, ***E.W. Jones***, *T. George,* JPL-California Institute of Technology; *M.L. Tuma,* NASA-Glenn Research Center; *R. Hansler,* Lighting Innovations-John Carroll University

A miniature,Si chip-based, incandescent light source utilizing tungsten filaments is being developed for integration into fiber optic systems to wavelength multiplex a suite of fiber-optic sensors operating in harsh environments from -50 C to 600 C. The requirements for the light source are that it operate at 2800 K, with an output power >100 mW in the 500-900 nm spectral band with spectral power variance of no more than 4% over the spectral band. In addition, it should be rugged, long-lived, with an

output stabilization time of about 1 second, and have a "footprint" comparable to LED devices. Other uses for these filaments are automobile headlights, and systems for vehicle navigation, in remote applications such as monitoring bridges for stress, and industial plant monitoring. To date, several filament fabrication approaches are being attempted. The first uses sputtered tungsten films (1-2 microns thick) patterned in various filament geometries. These filaments have been operated at < 2200 C) is the mounting of coiled-coil wire filaments on microfabricated Si chips. Lastly, 25-micron-thick W sheet stock is being patterned to produce planar spiral filaments. Filaments satisfying the above criteria will be packaged into a hermetically sealed three-chip stack consisting of a bottom reflector chip, a middle filament chip, and a top 5 mm x 5 mm SiN membrane optical window chip, integrated with an optical fiber. The fabrication procedures as well as the optical and electrical characterization results will be discussed in detail.

The Science of Micro-Electro-Mechanical Systems Topical Conference

Room 620 - Session MM+VT-ThA

Vacuum MEMS

Moderator: C.C. Wong, Sandia National Laboratories

2:40pm **MM+VT-ThA3 Quadrupole Mass Spectrometry using MEMS**, ***S. Taylor,*** University of Liverpool, U.K., UK **INVITED**

Quadrupole Mass Spectrometers (QMS) find a wide range of applications worldwide. The conventional QMS arrangement uses circular metallic rods as the mass filter excited electrically at voltages up to 1kV depending upon the application. If the size and voltages can be reduced then the range of applications for QMS instruments would increase. The application of MEMS technology allows the fabrication of submillimetre versions of such structures. In this paper the development of a miniature QMS is reported in which the conventional rod arrangement has been replaced with a microengineered version. The structure is made in silicon with metallised specially drawn glass fibres of length 20-30 mm and diameter 0.5 mm to act as the quadrupole rods. The correct electrode spacing and alignment are achieved through the use of V-shaped grooves etched into the silicon. This is about one order of magnitude smaller than most conventional QMS filters, with the potential for further reduction in size. The MEMS mass filter was mounted onto a commercial ion source, which was in turn attached to a vacuum flange and supplied by an electronic drive circuit modified to run at 6MHz. Mass spectra in the range 0-50 a.m.u were obtained and these were simulated numerically. The results indicate a linear mass scale with 5-10% valley separation between O2/N2 peaks and a best resolution at 10% peak height of around 2 a.m.u at mass 40. Reliable QMS operation was obtained up to pressures in the 1E-4 to 1E-3 mbar range and the highest operating pressure was felt to be a limitation of the ion source, rather than the mass filter.

3:20pm **MM+VT-ThA5 Miniaturizing an Ultra-High Vacuum Orbitron Pump**, ***J.Z. Wilcox***, *J. Feldman, T. George,* JPL-Caltech*; M. Wilcox, A. Scherer,* Caltech

NASA has identified the development of miniature vacuum pumps as a key future technology need. Miniature pumps will be needed for miniature instrument applications such as mass spectrometers and electron microscopes. Traditional pumps cannot be flown on microspacecraft due to their size, mass, and power requirements. This talk will discuss a novel approach towards the miniaturization of a particular type of high vacuum pump, known as the "Orbitron" pump. The Orbitron pump is an ion-getter pump that does not require magnetic confinement of the ionizing electrons. The purely electrostatic operation, coupled with a novel ring anode design under the development at JPL, enables miniaturization of the orbitron pump to sub-centimeter dimensions, and in addition may allow integration with instruments for in situ planetary exploration such as the Atmospheric Electron X-ray Spectrometer. The pumping action of the Orbitron pump is based on ionization of gas molecules by externally injected electrons which are trapped into stable helical orbits in a cylindrically symmetric electrostatic field around a positively charged anode. The ionized molecules are accelerated to the cathode and embedded in the surrounding collector. However, the conventional linear anode design does not lend itself to miniaturization very well since a minimum length of anode is required to establish stable orbits. The end losses are circumvented in the ring anode design, and in addition the "planar" geometry of the ring orbitron lends itself to miniaturization as well as ease in interfacing with other micro-instruments such as mass spectrometers, electron microprobes and electron microscopes. The goal of our effort has been to verify the feasibility and scalability of the proposed pump design. We will discuss the results of the validation experiments and modeling, impact on scaling to sub-centimeter dimensions, and compare the results with similar results for the linear anode orbitron.

3:40pm **MM+VT-ThA6 Scaling and Microfabricating a Low-Pressure Inductively Coupled Plasma Source**, *Y. Yin,* ***J. Hopwood,*** Northeastern University

Plasmas are commonly used in many large-scale systems. For example, chemical analysis using optical emission spectroscopy relies on gaseous plasmas to electronically excite the sample. Plasmas are also used as sources of radicals and ions for materials modification and for ion propulsion. In this presentation we will describe the miniaturization of plasma sources to dimensions that are compatible with MEMS. One of the most robust methods of generating a plasma is by inductively coupling an rf field to a low-pressure gas. Inductively coupled plasmas (ICPs) can operate for extended periods in reactive gas environments because ICPs are electrodeless. In addition, the geometry of the impressed rf field creates a high density of electrons with relatively low power consumption. A large-scale planar ICP uses a 10 to 30-cm spiral-shaped coil adjacent to a dielectric vacuum window; this geometry is particularly well-suited to microfabrication as the source is scaled down to dimensions the order of 1 mm. The scaling laws associated with miniaturization have been experimentally investigated in terms of optimum frequency of operation and gas pressure. In addition, the effects of scaling the dimensions on plasma properties such as electron temperature and electron density are also measured and modeled. The decreased dimensions of the coil reduces the inductance of the coil and necessitates a higher frequency of operation. Large scale ICPs typically operate at 13.56 MHz, but 5 mm ICPs function most efficiently at 300-400 MHz. Of particular importance is fabricating a coil with a high quality factor (Q) at the operating frequency. The optimum pressure for initiating the plasma is found to scale with the operating frequency such that the electron-neutral collision frequency equals the power supply frequency. Finally, the plasma sheath, or dark space, does not scale with the source dimensions. This appears to set a lower limit on the physical dimensions of the plasma source.

4:00pm **MM+VT-ThA7 Design and Fabrication of an Electromagnetically Driven Microvalve for Micro Total Analysis Systems**, ***M. Shoji,*** *K. Yanagisawa, M. Hirano,* Nippon Telegraph and Telephone Corporation, Japan*; S. Nakano,* NTT Advanced Technologies Corporation, Japan

Microvalves that control fluid flow over a wide flow rate range, and that are compactly assembled, are in great demand for µTAS, such as micro gas chromatographs. This paper reports on design considerations concerning the electromagnetic actuation and the fabrication of a microvalve that operates at a pressure difference of more than 1 x 10@super 5@ Pa with very low leakage. The valve is fabricated using silicon micromachining techniques.@footnote1,2@ The target specifications are a maximum flow rate of 10@super -1@ Pa m@super3@ s@super -1@, a leak rate of 10@super -9@ Pa m@super 3@ s@super -1@, a maximum power consumption of less than 0.1 W at a pressure difference of 10@super 5@ Pa, and a size of 4 x 4 x 2 mm including the actuation unit. The microvalve has a disk-shaped 1-µm-thick cap with a diameter of 100 µm. Actuation of the valve requires a force of more than 1.5 mN perpendicular to the surface of the cap and a stroke of 5-10 µm. To achieve this actuation, ferromagnetic material is deposited (electroplated) onto the cap and an electromagnet (1.3 x 1.5 x 3.2 mm) is set above the cap to generate an attractive force on the ferromagnetic material. The design parameters were determined by three-dimensional numerical analysis that took account of the nonlinear B-H curves of magnetic materials. When the deposited material was Ni with a thickness of 100 µm, and the distance from the Ni to the magnet was 20 µm, a sufficient force was attained if the formed Ni area was several times larger than the cap area. The analysis also showed that using materials with a higher saturation magnetization than Ni would increase the force, thus enabling the valve to work at a higher pressure difference. The effects of such materials will also be reported. @FootnoteText@ @footnote1@K. Yanagisawa, H. Kuwano, and A. Tago, Microsystem Technologies 2, 22 (1995). @footnote2@M. Hirano, K. Yanagisawa, H. Kuwano, and S. Nakano, Proc. IEEE Micro Electro Mechanical Systems, p. 323 (1997).

4:20pm **MM+VT-ThA8 MEMS Micro-Valve for Space Applications**, ***I. Chakraborty***, *W.C. Tang, D.P. Bame, T.K. Tang,* Jet Propulsion Laboratory

We report on the development of a Micro-Electro-Mechanical (MEMS) valve that is designed to meet the rigorous performance requirements for a variety of space applications, such as micro-propulsion, in-situ chemical analysis of other planets, or micro-fluidics experiments in micro-gravity. These systems often require very small yet reliable silicon valves with extremely low leak rates and long shelf lives. Also, they must survive the perils of space travel, which include unstoppable radiation, monumental shock and vibration forces, extreme variations in temperature. Currently, no commercial MEMS valve meets these requirements. We at JPL have developed a piezoelectric MEMS valve which attempts to address the unique problem of space. We begin with proven configurations which may seem familiar. However, we have implemented some major design innovations which should produce a superior valve. The JPL micro-valve is expected to have an extremely low leak rate, little susceptibility to shock, vibration or radiation, as well as a wide operational temperature range.

4:40pm **MM+VT-ThA9 Compact Fiber-Optic Pressure Sensors Using Microfabricated Sensing Membranes**, ***Y.C. Cho,*** NASA Ames Research Center*; T. George, J. Tamayo,* Jet Propulsion Laboratory

Fiber optic sensors are inherently immune to electromagnetic noise, and are very sensitive, light weight, and highly flexible. A prototype optically-detected pressure sensor was successfully designed, assembled and tested. The sensing technique employed was fiber- optic Fabry-Perot interferometry. The sensing head is composed of an optical fiber terminated in a miniature ferrule with a thin, silicon-microfabricated diaphragm mounted on it. The optical fiber is a single mode fiber with a core diameter of 8 microns, with the cleaved end positioned 50 microns from the diaphragm surface. The diaphragm is made up of a 1.5 mm square, 0.2 mm thick silicon nitride membrane whose inner surface is metallized with layers of 30 nm titanium, 30 nm platinum, and 200 nm gold for efficient reflection. The measured differential pressure tolerance of this diaphragm is more than 1 bar, yielding a dynamic range of more than 100 dB. Preliminary tests have demonstrated excellent performance for this sensor. Sensitivity measurements of the sensor were compared with that for a 3 mm diameter B&K microphone and were found to be 2 to 4 dB better than the B&K microphone. This sensitivity is better than any existing fiber optic pressure sensor by at least three orders of magnitude. The frequency response of the fiber-optic microphone was steady and uniform within the 100 to 5,000 Hertz design frequency. The compact size and light weight of these sensors gives them several advantages. For measurement of air flows over flight surfaces, the flow-sensor interaction is smaller, providing more accurate measurements of dynamic pressure. Additionally, their small size could allow these sensors to be placed non-destructively on flight surfaces in contrast to present techniques. The fiber optic microphone also has the added advantage of high temperature tolerance, and a solid state preamplifier as in the case of the condenser microphone is not required.

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