SYMPOSIUM EE
Materials Science of Microelectromechanical System (MEMS) Devices III
November 26 – 28, 2000

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The first part of the tutorial will provide an overview of the technologies and processes available for creating MEMS using surface and bulk-micromachining. In the second part, special "hot topic" discussions on BioMEMS and MicroOptics will be presented.

The morning section on fabrication will cover photolithography, thin film deposition, wet and dry etching, including extensive discussions of deep reactive ion etching and wafer bonding. Best practices in each of these areas will be highlighted. After lunch, the BioMEMS section will highlight new research areas including drug delivery systems, cellular analysis, surgical microtools and microfluidic devices. The MicroOptics section will emphasize trends and future prospects in optical communications. MEMS optical device characteristics and system architectures will be discussed.

Instructors:
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SESSION EE1: METhOLOGY
Chair: Maarten P. de Boer
Monday, November 27, 2000
Room 206 (Hynes)

8:30 AM *EE1.1 WHY MEASURING CONSTITUTIVE PROPERTIES IN MEMS DEVICES IS HARD, AND WHAT WE CAN DO ABOUT IT.
Stephen D. Sceurman, Massachusetts Institute of Technology, Department of Electrical Engineering and Computer Science, Cambridge, MA.

The world of microfabrication conjures up an image of infinite dimensional precision on microscopic scales. Unfortunately, this image is inaccurate. As a percentage of dimension, the precision with which components of microelectromechanical systems (MEMS) can be fabricated is typically orders of magnitude worse than for macrofabricated macro-scale components. This creates several questions for constitutive property measurement: (1) Metrology—how can we determine the actual dimensions of the specimen we are testing? (2) Modeling—how can we efficiently model the real structure, rather than an idealization of that structure? And (3) Error checks—how can we test our data for accidental inclusion of systematic errors in measurement? The key to all three questions is the same: extract constitutive properties from measurements on a set of devices with systematically varied dimensions. The approach will be described with examples drawn from measurements of residual stress and elastic constants of thin-film materials using membrane local-deflection methods, electronic pull-in measurements, and resonance frequency shifts.

9:00 AM *EE1.2 MICROELECTROMECHANICAL DEVICES FOR FORCE MEASUREMENT.
Thomas Kenny, Stanford Univ., Dept. of Mechanical Engineering, Stanford, CA.

In recent years, many researchers have adopted lithography, deposition and etching techniques from the IC processing community to the fabrication of microelectromechanical sensors. Many of the signals that these sensors are intended to detect are expressed as forces which stress or deflect the microelectromechanical structure. As sensors are miniaturized, these forces naturally become smaller, and techniques for detection are required to improve. Our research group has been engaged in a variety of activities, all of which share an interest in improving the force detection capability of microinstruments. In this talk, an overview of these activities will be presented, beginning with simple strain-gauge sensors (microwinches), sensors based on tunneling displacement transducers (nanowinches), AFM cantilevers (piconewtons), and ultrahigh force sensing cantilevers (atmospheres). Opportunities for exciting scientific measurements will be highlighted, and challenges for application of MEMS devices to these measurements will be discussed.

9:30 AM EE1.3 TEMPERATURE-DEPENDENT INTERNAL FRICTION IN SILICON NANOELLIOTROMECANICAL SYSTEMS.

The mechanical properties of micro- and nanomechanical systems are of interest from both fundamental and technological standpoints. High-frequency mechanical resonators presenting high quality factors are of interest for the development of sensitive force detecting devices, and highly efficient RF electromechanical filters and oscillators. Mesoscopic dimensions and high frequency operation also open fascinating possibilities for sensitive studies of extrinsic processes such as surface and near-surface effects, and of other fundamental phenomena. Internal losses are the combination of both extrinsic and intrinsic issues that must be well understood for the optimization of resonator quality, and for the experimental access of such mesoscopic mechanical phenomena. Nanomachining opens new avenues for the array of structures whose dimension compare to typical nanostructural length scales. We have recently reported the fabrication and electronic operation of nanomechanical beams as thin as 30 nm and frequencies as high as 380 MHz. We have also reported the dynamical modeling and characterization of pindle oscillators operating in the 1-10 MHz range. Here we report the temperature dependent behavior of these pindle oscillators. Reduction of temperature leads to an increase of the resonant frequencies of up to 6.5 %. Quality factors as high as 1000 and 2500 are observed at room temperature in metalized and nonmetalized devices, respectively. Although device mechanical insertion increases the overall level of dissipation, internal friction peaks are observed in all devices in the T = 160-180 K range. The position of these peaks is consistent with the Debeye relaxation of previously reported surface and near-surface in a. This to our knowledge the first reported observation of a Debeye relaxation peak in a megahertz range nanomechanical structure.

9:45 AM EE1.4 MEMS TECHNOLOGY USING RESONANT STRUCTURES.
A. Miller Allen and George C. Johnson, University of California, Dept. of Mechanical Engineering, Berkeley, CA.

A method for determining geometric process errors from the resonant frequencies of simple MEMS structures is presented. The ability to accurately determine the size of built geometry of MEMS devices is important given the magnitude of the geometric uncertainty relative to the dimensions of these devices. Consider a 2 µm square beam with 0.1 µm uncertainty in width or thickness. The relative uncertainty in both width and thickness is 5% and the associated uncertainty in the beam stiffness is even larger - on the order of 15%. As MEMS become smaller, the need for reliable metrology becomes even more important.

In an ideal process, the thickness and in-plane width of a MEMS structure would be exactly as specified in the design, and the size deviations of the structure would correspond to the dimensions on the film. Actual MEMS structures, of course, differ geometrically from the ideal. The method presented here provides a way to determine the actual film thickness, the etch offset (the difference between the design width of a linear feature and the as-built width) and the average angle of the side-walk. An important feature of the approach presented is that by using frequency ratios for various structural modes, neither the elastic modulus nor the mass density of the film need be known.

SESSION EE2: MECHANICAL PROPERTIES
Chair: Michael Judy
Monday, November 27, 2000
Room 206 (Hynes)
Aeronautical Laboratories, California Institute of Technology, Pasadena, CA.

Experimentation and testing of thin films require a thorough understanding of the behavior of test structures and their long-term stability and integrity. Surface roughness described by groove formation at the grain boundaries or on individual grains is distinctly dependent on the HF release time and on residual stresses in the film. The post-processing HF release has also been identified as an important parameter in the measurement of film properties. The surface roughness is a measure of roughness or fracture toughness or induce errors into elastic modulus measurements. Other phenomena are described, pertaining to wet release, which can be significant for the long-term integrity of MEMS structures.

11:15 AM EE2.3
MECHANICS OF FATIGUE IN POLYSILICON MEMS
STRICT STRUCTURE, ROY, O. Schuhrke, ET AL.
Aircraft Engineering, Princeton, NJ; Brian Gally, Stuart Brown, Exponent
Failure Analysis and Associates, North, MA.

This paper presents the results of an experimental study of fatigue crack nucleation and propagation in silicon MEMS structures. Following an initial description of the initial surface topology and nano-scale microstructure of polysilicon, the microstructures of crack nucleation and propagation are elucidated via in situ atomic force microscopy examination of cyclically actuated comb-drive structures fabricated from polysilicon. Mechanism-based models are then described that address the prediction of surface topology evolution and environmentally-assisted crack nucleation. The implications of the results are discussed for the extinction of polysilicon MEMS reliability within a mechanism-based or purely statistical framework.

11:30 AM EE2.4
FATIGUE OF THIN METAL FILMS INVESTIGATED BY DYNAMIC MICROBEAM DEFLECTION, R. Schütte, and O. Kraft, Max-Planck-Institute for Metallforschung and Forschungsinstitut für Metallkunde, Universität Stuttgart, Stuttgart, GERMANY.

Fatigue is a threat to metallic components in many technological applications. However, the role of fatigue in the reliability of micro systems has yet been explored in detail. This is probably due to the fact that most micro-electro-mechanical systems are based on Si in which fatigue is not expected to be a problem, as long as there are no initial cracks present. However, the use of metallic components in such systems can make them vulnerable to fatigue failure. In MEMS, metal films can be used for switches, valves or similar devices due to their magnetic properties or high electrical and thermal conductivity.

In this study, we have investigated fatigue in thin sputter-deposited Cu and Ag films with thicknesses in the range of 0.3 to 1.5 µm on micromachined silicon oxide cantilever beams. For fatigue testing, the beams were cyclically deflected for up to 4 million cycles with a frequency of typically 45 Hz using a nanonucitation system. During the fatigue tests the stiffness of the microbeams was continuously monitored and the occurrence of fatigue damage was detected as a significant decrease in stiffness. This damage was related to the formation of fatigue damage, such as extrusions and cracks, in the film, which would lead to a severe degradation of its functional properties. Lifetimes of the films were determined as a function of straining conditions and film thickness. As expected, the fatigue life decreases with increasing mean strain or strain amplitude.

Furthermore, it was observed that thinner films appear to be more fatigue resistant than thick films. The formation of extrusions is also less pronounced in the thinner films. The ultimate aim of these studies is to obtain a fundamental understanding of fatigue mechanisms in small volumes which is required for a thorough reliability assessment of metal-based MEMS.

11:45 AM EE2.5
FATIGUE EFFECTS IN THIN METAL PLATED CANTILEVERS FOR MEMS, Randall L. Kuhn, Deborah J. Kirby, Frederic P. Strohman, Richard J. Joyce, David T. Chang and Jinsoo Kim, HRL Laboratories, Malibu, CA.

During the past several years, we have developed high displacement sensitivity tunnelling interferometers and ultra-micron imaging and metal etching techniques. These devices consist of a Au tunneling tip fabricated below a 1 to 2 µm thick metal cantilever beam of evaporated Au or Ni. A thin film of beam evaporated Au on the underside of the cantilever serves as a tunneling counter electrode. In operation, a 100 nA bias is applied across the tunneling gap. A large turn-on voltage is also applied between the cantilever and a control electrode located on the substrate to deflect the cantilever, and the current is monitored. As expected, the tunneling current is about 1 or 10 nA. Typical deflections of the end of 100 and 250 µm long cantilevers are 0.5 µm during operation. We have observed the turn-on voltage as a function of time for different cantilever materials, tunneling currents, cantilever proeess, cantilever lengths, and with and without a low temperature vacuum anneal. We have observed that the turn-on voltage decreases over time for most devices with a larger drop observed for the Au cantilevers. The temporal dependence of the turn-on voltage was found to be temperature dependent. In addition, in all cases, this initial decay of the turn-on voltage was almost completely recoverable after the device was turned off for 24 hrs. This decay was not found to be strongly dependent on the tunneling current, but could be significantly reduced by pre-treating the cantilever before operation. Finally, a vacuum anneal at 200°C could influence the measured temperature dependence of the turn-on voltage. The observed effects appear to be consistent with fatigue and creep phenomena in the cantilevers. These effects are reversible at room temperature and are dependent on the stress and temperature history of the devices. We will present the device data, the detailed measurements, and some of our initial conclusions in this paper.

SESSION EE3: TRIBOLOGY
Chair: S. Mark Spearing
Monday, November 27, 2000
Room 206 (Hynes)

1:30 PM EE3.1
SURFACE ENGINEERING OF POLYSILICON-BASED MEMS, Roy Mohamed, Dept. of Chemical Engineering, Berkeley, CA.

Given the dimension of most micro-electro-mechanical systems, gravity and other body forces are negligible. In contrast, interfacial forces dominate due to their large surface-to-volume ratios. As a consequence, adhesion, friction, and wear are prevalent problems in micro-MEMS devices. Additionally, MEMS technology provides with the opportunity to study tribology in the mesoscopic length scale. This presentation will discuss the use of several tribological microinstruments in conjunction with other surface characterization techniques, such as X-ray photoelectron spectroscopy and atomic force microscopy, to measure the surface forces present between polycrystalline silicon surfaces and to manipulate them by utilizing various surface treatments. The successes and the limitations of currently available nano coatings technologies as well as areas for improvement will be discussed.

2:00 PM EE3.2

Understanding the effects of surface roughness on parameters such as adhesion, friction, and wear is a central question in the tribology of MEMS. In this work, we have fabricated polysilicon cantilevers over terraces of surfaces of varying roughness, and examined the effects of the interfacial adhesion of the cantilevers to the surfaces. A hydrophobic monolayer lubricant is applied to the surfaces to eliminate the effects of capillarity. Adhesion is measured by a well-developed fracture mechanics approach, in which the beam deflections are quantified, and the energy release rate is equated with the interfacial adhesion.

Contrary to expectations, the effects of roughness, when increased over a large range from 3 to 12 nm rms, reduced the adhesion only from 8 to 5 microjoules per square meter. We believe this weak dependence is a fundamental result for nanotextured surfaces. Namely, real contact areas are exceedingly small, on the order of tenths of the apparent contact areas. However, because of the planar micromachining techniques in MEMS, the average surface separation is also small. Therefore, van der Waals forces between non-contacting areas dominate the interfacial adhesion. The average separation does not depend strongly on surface roughness because plastic deformation of asperities tends to reduce the initial separation. To investigate this line of thinking, we have quantified the surface topography by atomic force microscopy. The results are fed into a finite element program that includes the effects of surface forces as well as material plasticity, and the surfaces are meshed in the computer. We expect this modeling will exhibit a length scale dependence on sample area, and at large sample areas, the dependence on roughness should converge. 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.

2:15 PM EE3.3
NOVEL CHEMISTRY FOR SURFACE ENGINEERING IN MEMS, Xingyong Zhu, Department of Chemistry, University of Minnesota, Minneapolis, MN.

It is well recognized that controlling surface forces is one of the key
issues in the design, fabrication, and operation of micro-
electromechanical systems (MEMS). Since the majority of MEMS
devices are made of silicon from the surface micromachining,
an attractive approach has been the use of well-known alkyl trichlorosilane
self-assembled monolayers (SAM) on oxidized silicon surfaces
to control surface energy. While this approach has enjoyed some success
in reducing adhesion in model MEMS structures, a major impediment
to its implementation in a manufacturing setting is that it is highly
irreproducible and very sensitive to a number of experimental
parameters. In this report we present a novel strategy for the
efficient assembly of self-assembled monolayers directly on oxidized
silicon surfaces via Si-O linkages. This is achieved by the reaction between an alcohol
functional group and a chlorinated Si surface. The resulting molecular
monolayers are uniform and chemically stable and are successfully
demonstrated in adhesion reduction in a model MEMS structure,
namely, a cantilever beam array (CMA). Polycrystalline beams with
length up to 1.5 mm can be realized. Major advantages of this new
approach for surface control in MEMS include simplicity,
reproducibility, and reliability.

2300 PM EEE-3
THE FRICTION AND WEAR RESISTANCE OF TUNGSTEN
COATINGS ON SILICON MICROMACHINED DEVICES RELATED
TO THEIR SURFACE CHEMISTRY. M.T. Daguer, S. Mati, D.E.
Peebles and G.A. Poukey, Sandia National Laboratories,
Albuquerque, NM.

As processing technology for polysilicon surface micromachine devices evolves, design of actuators with Mn-range force output and
structures with high out-of-plane stiffness has become possible. These
structures reveal susceptibility to micro and nanoscale adhesion during the
release etch that is not seen with their predecessors. However, in mechanical systems that rely upon the contact of moving surfaces to perform their
function, a better understanding of friction and wear is needed to predict the initial performance as well as the performance of the devices
age. To this end, we have investigated the relationship between
surface chemistry, friction and wear for CVD tungsten coatings applied
to polysilicon surface micromachined devices. The evolution of surface chemistry of the coatings from time of deposition to two weeks following deposition was examined using X-ray photoelectron spectroscopy. The tribological behavior of the coating was determined using a specially-constructed micromachined friction tester that permits quantification of friction forces between vertical sidewall surfaces. Results show that the initial composition of the tungsten coating consists of more than 40 atomic percent tungsten, but within a week of deposition the surface composition is dominated by
adsorption of carbon and growth of oxide on the tungsten films. At this
time, the coatings exhibit a friction coefficient less than 0.10 and
no measurable wear after a million cycles of sliding contact in air.
This paper will report on the relationship between composition and
tribology of tungsten coatings for MEMS, and the mechanisms
responsible for the observed friction and wear behavior. We will also
discuss the effect of the oxygen and water vapor content in the
operating environment on tribological behavior of these coatings.

2450 PM EEE-5
ADHESION AND STATIC FRICTION MEASUREMENTS IN LIGA
MEMS CONSTRUCTION USING NOVEL NANOSTEAD TECHNIQUES. Somuri V. Perumal, David A. LaVine, Todd R.
Christensen and Mike T. Daguer, Sandia National Laboratories,
Albuquerque, NM.

LIGA, which combines synchrotron radiation lithography,
galvanomasking and plastic molding, is an emerging technology for
producing net-shape components and structures for micro-
electromechanical systems (MEMS). LIGA processed structures can be
made of different materials such as metals (e.g., Ni and Cu), alloys
and composites, deposited from suitable electroplating baths. Like in other silicon based MEMS, adhesion plays a vital role in the
performance of a LIGA processed MEMS device. The objective of our
study was to characterize the adhesion and static friction between
LIGA structures at length scales relevant to MEMS applications using
novel nanoindentation techniques.Indentors of known radii of
curvature, suitable for nanoindention experiments, were fabricated
using the LIGA process. The Berkovich diamond indenter was
replaced with LIGA fabricated metal tip, and the indentation
experiments were performed on LIGA dies. The pull-off force (i.e.
the negative load required to separate the LIGA tip from the flat surface
after contact) was measured from the indentation experiments. The
effects of applied load, surface topography, presence of oxide layers on
the pull force were evaluated. The setup was also used to perform
static friction measurements at length scales relevant to LIGA MEMS.

This paper reports on the design, fabrication, and properties of a MEMS (micro-electromechanical systems) accelerometer using lead zirconate titanate (PZT) 9/8/48 films as the active sensing element. The design is an in-piezoelectric version of a 4 mm thick film on a Pt/Ti/SiO2/Si cantilever structure with a large Si proof mass. The sol-gel PZT films show good dielectric and piezoelectric properties, with P, values > 20 pC/Nm, ε, ∼ > 800, tan δ < 3%, and -d33 - values > 10 pC/N. A 4° design variant using the PZT film was made, a high extraordinary strain, as the cantilever release step, was accomplished via deep reactive ion etching of the Si substrate. It was found that for accelerometer with a footprint of 1 cm2, it is possible to achieve a charge sensitivity as high as 1.04 pC/g. Work is currently ongoing to optimize the output of the sensor, as well as to characterize the temperature dependence of the response. This work is supported by a NSF ATP program.

4:15 PM EE4.4 DEFECTS AND FAILURE MODES IN PZT FILMS FOR A MEMS MICROENGINE. D.F. Bier, B.T. Grenier, C.D. Richards and R.F. Richards, Mechanical and Materials Engineering, Washington State University, Pullman, WA.

Piezoelectric films for a MEMS microengine have been deposited using solution deposition routes onto silicon wafer. These films are used as membranes above bulk micromachined cavity. A dynamic bulge test and interferometer are used to characterize the deformation of the films when pressurized. The mechanical stress at failure, as well as the fatigue behavior, have been characterized. Membranes between 1 and 4 microns thick have been shown to sustain over 350 million cycles at stress levels between 70 and 90% of the mean failure stress in the films due to material fatigue. Growth and thermal stresses during processing, and their role in membrane failure, are identified. The effect of these defects on the electrical behavior of the films is also discussed. The results of the bulge test failures are compared to indentation induced failures and thermally induced failures which generate interfacial failure between the metalization layers and the underlying silicon oxide.

4:30 PM EE4.5 EXCITED LASER LIGHTFF: AN ALTERNATIVE INTEGRATION SCHEME FOR FABRICATING Ph(Zr, Ti)Ox-BASED MEMS. Leena Taskinen, Alberto Salfo, William S. Wong 8 and Tim Sands, University of California, Berkeley, CA; Pamela Carson and Richard M. White, Univ of California, Berkeley Sensor & Actuator Center and Dept of Electrical Engineering & Computer Science, Berkeley, CA; and at Xerox Palo Alto Research Center, Palo Alto, CA.

In recent years a wide variety of piezoelectric MEMS sensors and actuators have been demonstrated. Initial devices utilized ZrO thin films that are relatively thick and therefore failing devices in the thin film have injection currents of the order of microamps and limited useful lifetime. It is therefore no longer possible to use these piezoelectric MEMS sensors and actuators on chip. This problem is particularly acute for Ph(Zr, Ti)Ox-based MEMS devices. Ph(Zr, Ti)Ox-based MEMS devices have been demonstrated in a variety of configurations [1, 2]. However, the use of these devices in microfabrication processes has been limited by the lack of an effective integration scheme. This paper presents a new method for the integration of Ph(Zr, Ti)Ox-based MEMS devices. The method is based on the use of a thin film Ph(Zr, Ti)Ox film as an interlayer material. The film is deposited using a sol-gel process and then subjected to a high temperature anneal. The anneal results in the formation of a thin film Ph(Zr, Ti)Ox layer that is electrically active. This layer is then used as an interlayer material in the fabrication of the MEMS device. The use of this method results in a device that is electrically active and has a useful lifetime of several hundred hours.

SESSION EE5 POSTER SESSION

Chair: Maarten P. de Boer, Michael Judy, Hall Kahn and S. Mark Spearing

Monday Evening, November 27, 2000
8:00 PM
Exhibition Hall D (Hynes)

EE5.1 MULTILAYER MATERIALS FOR ELECTROSTATIC SWITCHES. Mark A. Phillips, Benjamin L. Peterson, Christine M. Fisher, Jesse Kwong, Bruce M. Clemens, Stanford University, Dept of MSEE, Stanford, CA.

Metal multilayers are a unique way to manufacture reliable conductive members for MEMS devices. These members are particularly suited for electrostatic switches. Unlike elemental Al, which experiences curvature problems during processing, the stress in these beams can be controlled and calibrated during the process. Stress measurements are important to determine the optimal composition and the thickness of the multilayer for a low contact resistance. The mechanical and electrical behaviors of metallic multilayers are investigated in order to develop reliable electrostatic switches for MEMS devices.

EE5.2 ELECTRIC FIELD TRAPPING OF BIOLOGICAL CELLS INTO MICRO-MACHINED CAVITIES. Cengiz S. Ozkan, Mahirinm Ozkan, Erhan Ata, Sadik C. Esener, Electrical and Computer Engineering Department, University of California at San Diego, San Diego, CA.

This paper describes a novel technique for trapping live biological cells into micromachined cavities or channels on flexible and transparent polymer substrates. The substrate is made of a silicon wafer and coated with a thin layer of polyimide. A polyimide film is then spin coated onto the silicon wafer and baked at 450 degrees Celsius for 30 minutes. The polyimide film is then patterned using photolithography and wet etching. The patterned polyimide film is then used to form a mechanical trap for live biological cells. The trapping mechanism is based on the fact that the cells are negatively charged due to the presence of the negatively charged protein layer on the surface of the cells. The cells are then trapped by applying a strong electric field between the two electrodes. The electric field is then used to hold the cells in place and prevent them from moving.
EES.3
RECENTIONS OF MEMBRANE STRESS USING ALUMINIUM OXIDE AND SILICON DIOXIDE MULTILAYER STRUCTURE
Ryuichi Kubo, Yuki Yoshino, Kazuyoshi Hase, Takehiko Makino, Seiji Ariy, R&D Division, Maruhana Mfg. Co., Ltd, Kyoto, JAPAN.

Relaxation of internal stress for micro-electro-mechanical systems (MEMS) using multilayer thin films which are made of Al_2O_3 and SiO_2 has been studied. The relaxation of internal stress is necessary for MEMS devices, such as membrane devices, because the stress causes deformation of its structures. This work is focused on aluminium oxide thin films that have tensile stress and silicon dioxide thin films that have compressive stress were combined to make a low stress membrane. The aluminium oxide thin films were prepared by electron beam evaporation at room temperature, and the deposition rate was about 50nm/min. No peaks were observed in the X-ray diffraction pattern of the films. The composition ratio of Al and O kept the same ratio of Al_2O_3 target material. The internal tensile stress was about 400 MPa. The silicon dioxide films were prepared by thermal oxidation and RF magnetron sputtering method. The internal stress of thermal oxide films was about 400 MPa and that of the films deposited by sputtering was about 100 MPa. These silicon dioxide thin films and aluminium oxide thin films were prepared in multilayer on Si(100) substrate, which was then backside etched to form a membrane structure of 1.6 mm square. The thickness of each film was controlled for reducing the total stress of the membrane. The total stress of the membrane was almost 0 in optimum deposition condition of SiO_2 and Al_2O_3 films.

EES.4
STRESSES AND DEFORMATION IN MINIATURE STRUCTURES AND MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS)
T.A. Venkatesh and S. Suresh, Dept. of MSEE, Cambridge, MA.

The optimization of electromechanical, thermal, optical, fluidic or magnetic functionality of MEMS devices requires a comprehensive understanding of a variety of materials and mechanical issues, particularly those dealing with the prediction, measurement and control of processing-induced and service-induced stresses as well as mechanical performance. A comprehensive analysis of stresses and deformation in small-volume structures requires a full consideration of several factors such as geometry, combination of materials used and the processing sequence adopted in fabricating these structures, and the chemical/thermo-mechanical environmental interactions that these structures are expected to encounter while in service, all within the context of length-scale dependence of fundamental elastic-plastic mechanical properties. Thus, a prediction of the overall mechanical response of a particular structure would typically mandate a tracking of all aspects of a given structure through fabrication and service. Hence, an alternate approach is presented here, whereby small-volume structures are classified based on their geometry, structural environment, and coupling characteristics, and a general framework for the analysis of the mechanical response of such structures is constructed and analyzed. In parallel with this classification, a broad and complementary classification of experimental techniques that enables the extraction of the fundamental properties of materials is also developed. Key results of the various methods for elastoplastic, failure and fatigue analysis are reviewed and advantages and limitations of each method are analyzed. General trends in material properties at small size scales are discussed in the light of available results as well. Particular examples are also presented of situations where such powerful methods for the study of mechanical response in miniature structures.

EES.5
YOUNG'S MODULUS AND STRENGTH OF THREE POLY-SILICON
W.N. Sharpe, Jr., K. Jackson, G. Cola, Johns Hopkins University, Dept. of Mechanical Engineering, Baltimore, MD; D.A. LaVan, Sandia National Laboratories, Albuquerque, NM; R. Mishi, Standard Membrane Inc., Haspugny, NY.

Structural materials of a certain class, e.g. aluminum, have essentially the same Young’s modulus, but different strengths depending upon manufacturing process. One wonders if the same rule is true for materials used in MEMS. The authors have developed tensile test techniques and procedures for measuring Young’s modulus and strength of polysilicon and have used the same test apparatus to test materials from different sources. The tensile specimens were deposited onto silicon wafers, one end of each specimen is fixed to the wafer and its test section along with a one-millimeter square grip end is released by etching away an underlying sacrificial layer. An electronic readout of the grip end, and the specimen is pulled by an electrostatic translation stage. Force is measured with a 1000g load cell, and overall system displacement is measured with a capacitance probe. Young’s modulus is extracted from the force-displacement data using a finite element model of the specimen and the measured stiffness of the gripping and loading system. Polysilicon from Cronos, Sandia, and Standard Membrane, Inc. (SMI) were tested, with the latter supplying two sets of wafers that had been processed differently. The specimen dimension of the SMI material was nominally 6 or 20 mm wide and either 250 or 1000 mm long. The Cronos and the Standard Membrane specimens had thicknesses of 1.5, 2.0, and 3.5 mm; whereas, the Sandia specimens were all 2.5 mm thick. There was no statistical difference in Young’s modulus for the three materials. A total of 117 tests were run, and 45 tests of the Cronos material yielded a value of 1.58 ± 0.8 GPa. However, the residuals were quite different between Cronos and Sandia at 0.56 ± 0.25 GPa. The Cronos and Sandia tests at 3.0, 0.18 GPa, 20 tests of each type yield stresses at 2.08 ± 0.35 GPa, and 24 tests of the other SMI type at 2.00 ± 0.25 GPa. These results will be presented in detail along with a description of the test methods. Continuing research to determine the differences in strengths will be presented if time permits. This is the first direct comparison of polysilicon from different suppliers, and the fact that the strength can differ by a factor of two is important. This research was conducted under the sponsorship of DARPA.

EES.6
STRAIN HARDENING, STRENGTHENING AND NEW TESTING OF SURFACE MICRO-MACHINED MEMS
D. A. LaVan, K. S. Jackson, M.T. Dugger, P. M. de Boer, J. P. Sullivan, T. A. Friedmann, Sandia National Laboratories, Albuquerque, NM.

Simple, quick and accurate methods to measure and qualify material properties are necessary for surface micromachining to be accepted as a standard manufacturing technique for critical components. The results from ongoing large-scale single studies of polycrystalline and amorphous Diamond (a-D) strength testing will be presented. Fracture toughness is being investigated using two techniques: FIB notched tension samples, and an electrostatically actuated device capable of applying cyclic loading (up to 2 GPa principal stress at a notch root) followed by a final high force loading cycle. Results for polycrystalline and a-D will be presented for the notched samples, and for polycrystalline only using the 5-level fracture toughness measurement device. New devices to directly probe strength using electronic actuation and interferometric microscopy will also be shown. Wear and adhesion limits the life of many devices. A device proven in wear studies of polycrystalline has been modified for the a-D process; results for the wear of a-D will be shown.

EES.7
MICROSTRUCTURE, STRENGTH AND PIN-ON-DISC WEAR TESTING OF LIGA MEMS

LIGA manufactured MEMS devices are being rapidly adopted as their length scale is close to conventional miniature devices. However, few miniature components, manufactured using conventional techniques, are made from the pure metals or alloys used in LIGA devices. The lack of LIGA materials is expected to be a significant barrier to the development of LIGA-based engineering alloys. This work will summarize a large study completed on the process-microstructure-properties of LIGA Nickel, as well as introduce new results for Nickel Alloys and Nickel nanocomposites. The new materials offer the promise of more over extended temperature and more favorable tribological behavior. They have been characterized using a suite of analytical tools including nondistortion, pin-on-disc wear testing, AFM, miniature tensile testing, metallography, and EBID imaging of orientation.

EES.8
BEHAVIOR OF MICRON-DIMENSION SILICON GERMANIUM STRUCTURAL FILMS UNDER CYCLIC LOADING
Christopher Muhlstein, University of California, Department of Materials Science and Engineering, Berkeley, CA; Andre Franke, Roger Howes, University of California, Department of Electrical Engineering and Computer Sciences, Berkeley, CA; T. Ritchie, University of California, Department of Materials Science and Engineering, Berkeley, CA.

Unlike their macroscopic counterparts, microelectromechanical systems (MEMS) have seen the immediate application of brittle structural materials in safety-critical applications, such as airbag accelerometers and inertial guidance systems. In spite of the risks, the use of diamond-like carbon films such as silicon will persist because of the large base of processing expertise and equipment, as well as the ease of integrating electronics. However, due to the real potential for premature failure, the long-term use of brittle structural films such as silicon mandates the investigation of subcritical crack growth phenomena such as cyclic fatigue and stress corrosion cracking. The ongoing work of the authors [Muhlstein and Ritchie] has enabled the identification of time-delays for failure in thin films in under 1 x 10^2 cycles at approximately one half the single cycle strength of the material. Recent advances in SiGe-based surface
micromachining at the Berkeley Sensors and Actuators Center (BSAC) have prompted this investigation of the behavior of SiGe structural materials under cyclic loading conditions. Intermediate compositions of p-type SiGe-based films have been successfully surface-micromachined with integrated CMOS electronics (Franke and Howe). This recently developed processing technology was used to manufacture test structures, which were characterized by fatigue testing structures previously developed at Exponent, Inc. Initial testing indicates that the SiGe structural films have comparable strength to polysilicon silicon films. However, the concept of SiGe films for time-delayed failure under cyclic loading conditions has not been previously demonstrated. The stress-life behavior of the SiGe films in ambient environments will be presented in conjunction with a detailed characterization of fracture surface morphology using the scanning electron and atomic force microscopy (SEM and AFM). This investigation provides the first comparison of the behavior of SiGe to existing polyimide films under cyclic loading conditions and is a critical milestone in the introduction of novel structural film material systems.

EES.9
FINITE ELEMENT ANALYSIS OF THE PRECRACKED LINE SCRATCH TEST. LL. Mercado1, 2, A.A. Volinsky, V. Swami, W.W. Gerberich2, Motorola Inc., Interconnect Systems Laboratories, Tempe, AZ. University of Minnesota, Dept. of Chem. Engineering and Material Science, Minneapolis, MN.

In MEMS devices and packages, the interfacial adhesion is a critical reliability issue. A Pre-cracked Line Scratch Test (PLST) is among one of the available tests to measure the thin line adhesion. In the test, an initial crack is introduced at the interface between the thin line and the substrate. The line is then loaded in a pre-cracked end. The load is recorded continuously while the crack propagates before and after the line is pre-cracked. The pre-cracked line scratch test has been applied earlier to the tungsten thin lines on silicon wafers [1].

Microscopic version of the test was also performed to evaluate the analytical model [2]. In the microscopic tests, polycarbonate lines are bonded to steel substrates with cyanoacrylate. In this study, finite element analysis is performed for the Pre-cracked Line Scratch Test prior to the line buckling. The energy release rate and phase angle are calculated based on the corresponding load and crack length. The results are then compared to the closed-form solution. Both the microscopic and macroscopic tests are evaluated. Finite element solution has provided a way to determine the interfacial fracture toughness as a function of the phase angle based on the load and crack length history. With the analysis in place, the pre-cracked line scratch test can be used conveniently to study the adhesion of MEMS devices and packages on different scales.


EES.10
DEFORMATION MECHANISMS OF A MICRO-SIZED AUSTENITIC STAINLESS STEEL WITH FINE GRAINS. Guangqing Zhang, Kazuki Takashima, Masayuki Shimojo, Yukihiro Higo, Tokyo Institute of Technology, P&I Laboratory, Yokohama, JAPAN.

With the rapid growth of micro-electro-mechanical systems (MEMS) with a high development cost, the demand for the understanding of the mechanical performance in micro-sized materials becomes more and more urgent in order to design highly reliable micro-sized machines. Previous studies on the mechanical properties of micro-sized materials mainly focused on the measurements of Young modulus and fracture strength. However, the basic deformation mechanisms of micro-sized materials, especially for the fine-grained materials widely applied to MEMS in the form of thin films, are still less well understood till now. In this study, a micro-cantilever beam type specimens with dimensions of 30 x 25 x 65 μm³ were fabricated from austenitic stainless steel sheet with 1 μm grain size by focused ion beam machining. The deformation behavior of such micro-sized specimens was studied by the static bending tests. The results showed that the micro-cantilever beam type austenitic stainless steel is of two-stage deformation processes, namely, rapid work-hardening of the stage I and subsequently slow work-hardening of the stage II. At the stage I, the deformation behavior is characterized by the extensive intragranular dislocation slips and their interaction with grain boundaries which led to the deformation incompatibility near grain boundaries and the appearance of the roughness on the specimen surface. With increasing in plastic strain, grain boundary sliding (GBS) and subsequently intragranular cracking occurred at the stage II. The differences in stress conditions and work-hardening behaviors on the two stages and near crack sites on the side surface of the micro-cantilever beam resulted in the different deformation behavior.

EES.11
CORROSION FATIGUE TESTS OF MICRO-SIZED SPECIMENS. Mari Minamiz, Yukihiro Higo, Yasuaki Ichikawa, Atsushi Morita, Kazuki Takashima, Tokyo Institute of Technology, P&I Lab., Yokohama, JAPAN.

Fatigue properties and long-term reliability of micro-sized materials are extremely important to design actual MEMS devices. In particular, the evaluation of fatigue properties of micro-sized components in corrosive environments is essential in micro-biocomedical devices, as the surface effect on the corrosion is more prominent than ordinary-sized components. However, there have been few studies to date which investigate corrosion fatigue properties of micro-sized materials, since there is no adequate corrosion fatigue testing equipment for micro sized materials. In this investigation, a corrosion fatigue testing machine for micro-sized materials has been developed. This testing machine was capable of applying very small cyclic loading to micro-sized specimens with a load resolution of 1 mN and a displacement resolution of 5 μm, respectively. The specimen stage and solution cell is set on a precise X-Y stage, which can be moved to adjust the loading position by a stepping motor at a translational resolution of 0.1 μm. Fatigue tests were carried out both in air and in 0.9% NaCl solution. Cantilever beam type specimens with dimensions of 10 x 10 x 50 μm³ were prepared from an Ni-P amorphous thin film and a type 304 austenitic stainless steel foil by focused ion beam machining. Small cyclic load is able to be applied to the specimens in the solution. Fatigue lives in both the specimens in corrosive environment was lower than that of in air. The effect of environment and that of specimen size on fatigue properties for micro-sized specimens are discussed.

EES.12
ANISOTROPIC FRACTURE BEHAVIOR OF ELECTRODEPOSITED Ni-P AMORPHOUS ALLOY THIN FILMS. Kyusuke Takashima, Akio Ogura, Yasuaki Ichikawa, Masayuki Shimojo, Yukihiro Higo, Tokyo Institute of Technology, P&I Laboratory, Yokohama, JAPAN.

Thin films deposited on substrates are expected to be applied to MEMS including biomedical and micro-photonics devices. In such devices, the film layer is machined into micro-sized elements by mechanical or chemical means. Therefore, the fracture behavior of thin films on substrates is extremely important to ensure the reliability of such MEMS devices. Thin films deposited on substrates have been considered to have an anisotropy even if they are amorphous films, and the fracture behavior in out-of-plane direction (perpendicular to the deposition growth direction) is anticipated to be different from that of in-plane direction (parallel to the deposition growth direction). Such an anisotropic fracture behavior of deposited films has not yet been clarified because of the difficulty in the testing method. In this study, fracture toughness tests have been performed for electrodeposited Ni-P amorphous alloy thin films with different crystal growth directions, which are perpendicular and parallel to the deposition growth direction. Cantilever beam type specimens with dimensions of 10 x 10 x 50 μm³ were prepared from an Ni-P amorphous thin film and notches with different loading directions introduced by focused ion beam machining. Fatigue pre-cracks were introduced ahead of the notches. Fracture tests were performed using a newly developed mechanical testing machine for micro-sized specimens. Fracture behavior is different between different types of specimens. Although Kc value were not obtained as the criteria of plane strain requirements were not satisfied for this size of the specimen, the specimen fracture toughness Kc value of the specimen with crack growth being parallel to the deposition growth direction was 4.2 MPa√m and that with crack growth being perpendicular to the deposition growth direction was 7.3 MPa√m, respectively. These results suggest that the electrodeposited amorphous alloy films have an anisotropy.

EES.13
TEMPERATURE AND DOPING DEPENDENCY OF PIEZORESISTANCE IN P-TYPE SILICON. Eivind Land, Terje Finstad, Univ of Oslo, Dept of Physics, Oslo, NORWAY.

We have performed new measurements of the temperature and doping dependency of the piezoresistance in p-type silicon. Piezoresistance is the change of resistance due to an applied mechanical stress. The effect is well known in silicon and is one of the most common sensing principles of micro-electro-mechanical systems (MEMS).

Our measurements are performed in a specially designed 4 point bending setup. The samples are 6 x 40 mm2 beams of full wafer thickness. To minimize leakage currents and to obtain uniform doping profiles we have used SIMOX (Separation by Implantation of Oxyger) substrate with a SiO2 epilayer layer. Spreading resistance measurements verify the uniform doping profile, while measurement of
zero stress resistance versus temperature verify low leakage current. Some of our samples even have resistors that are further isolated by dry etched trenches through the top silicon layer. In this paper we present results for the doping range from 1E17 Cm⁻² to 1E20 Cm⁻² and the temperature range from −80 to 150 degrees Celsius. The results show a doping dependency well described by the analytical expression

From this paper, we present results for the doping range from 1E17 to 1E20 Cm⁻² and the temperature range from −80 to 150 degrees Celsius. The results show a doping dependency well described by the analytical expression:

\[ E_{g} = C \frac{N_{d}}{A} \left( \frac{T}{T_{m}} \right)^{1/3} \]

Here, \( E_{g} \) is the Fermi integral, \( F_{g} \) is its derivative with respect to \( E_{g} \), \( F_{g}(E_{g}) \) is the Fermi energy at the doping level \( N_{d} \), and \( A \) is the Boltzmann's constant and \( T \) is the temperature. The temperature dependency of the piezoresistance coefficients fits a decreasing linear model where the absolute value of the temperature coefficient decreases with increasing doping.

We formulate a possible explanation to the deviation from current analytical models based on the temperature dependent change of the effective masses with applied stress. Previously published measurements of the effective mass show clearly how the effective mass changes under applied mechanical stress. The fractional change in effective mass is assumed to be strongly temperature dependent.

References:

**EES 14**

MULTISCALE MODELING OF DISPLACIVE PROCESSES IN MEMS RESONATORS. Robert E. Rudd, Lawrence Livermore National Lab, Livermore, CA; Jeremy Q. Broughton, Yale School of Management, New Haven, CT.

This work studies multiscala phenomena in silicon and quartz micro-resonators comprising the mechanical components of sub-micron Micro-Electro-Mechanical Systems (MEMS). The behavior of the next-generation MEMS will be largely dictated by the interplay between physics at the Angstrom, nanometer and micron scales. Atomic processes cause systematic deviations from the behavior predicted by conventional elatic theory, and lead to unconventional mechanisms for dissipation. The simulation of these effects is a challenging problem since they are coupled to long-range strain fields so that a large number of atoms are involved. We use molecular dynamics (MD) calculations to probe the most critical region of the devices, consisting of a few million atoms. Hundreds of megabytes are in the proximal regions of the substrate, but here the strain gradients are much smaller, and a more efficient description suffices. We couple MD to finite elements, or a nanoscale generalization. We have developed known as Coarse-Grained Molecular Dynamics (CGMD). In this way we capture the relevant physical effects at two length scales simultaneously. The nanoscale atomistic processes in the core of the devices, and the micro-scale elastic fields extending out into the substrate to which they are inherently coupled. In this talk we present simulations of the vibrational behavior of micro-scale oscillators, and focus on unconventional dissipation mechanisms at the nanoscale.

Acknowledgements:

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**EES 15**

PHASE TRANSFORMATIONS IN FERRIMAGNETIC NiMnGa SHAPE MEMORY FILMS, Mark Budzinski, Cornelius Cuculescu, Jie Jia, Univ. of Maryland, Dept. of Materials Science and Engineering, College Park, MD.

Recent work on aeronautical NiMnGa films sputtered on silicon cantilever substrates. The films are partially crystalline if the substrate is held at room temperature (RT) during the deposition. They become fully crystalline after annealing at 400°C. The internal friction (IF) of the RT deposition shows a peak that is attributed to the coarsening of the film. Films deposited at RT are coarse-grained and films deposited at 350°C show a transformation comparable to NiTi shape memory films. However, the damping is one order of magnitude lower. Annealing does not significantly change the phase transition of films that were deposited at 350°C, and the linear measurement show a dependence of the change of the elastic modulus as a function of the magnetic field of a nominally NiMnGa film suggest that the magnetic micростucture field increases proportional to the transformation strain, \( c/\alpha \)., from 5 volunteers at 50°C to 0.8 T at 10°C.

**EES 16**

EFFECT OF La ON THE GROWTH OF Cu2Sn IMETALLIC COMPOUND, Xia Jia, Hongyan Dong, Yiju Qian, Harbin Institute of Technology, Dept. of Material Science and Technology, Harbin, CHINA; Fanzhong Yoshida, Hiroshima University, Higash-Hiroshima, JAPAN.

The thickness of the Cu2Sn intermetallic compounds [1MC] layer has played an important role in the reliability of microelectronic packaging at PCB level. Previous experimental results showed that, with the increasing of the thickness of Cu2Sn IMC layer, both the thermal fatigue life and the fracture ductility of solder joints decreased. Therefore, depressing the growth of Cu2Sn IMC should be an effective method to improve the reliability of solder joints. In this study, small amount of the rare earth element La (only 0.005% by weight) has been added to traditional Sn60Pb40 solder alloy. The results of aging testing of solder joints showed that, after aged at 358K for 120 hours, the mean thickness of Cu2Sn IMC layer at the interface of solder joints decreased from 7.68µm to 5.6µm by adding small amount of La into solder alloy. Furthermore, the results of thermal cycling tests showed that, thermal fatigue life of solder joints improved 3 times compared to the case of the above experimental phenomenon, thermodynamic model has been introduced. At first, the calculating results of the interaction relation.
of constituent elements indicated that Ln has higher affinity with Sn in Sn-Ln system. Therefore, with the consideration that Cu will not react in a Sn-Ln quaternary system can be simplified to Cu-Sn-Ln ternary system. Thermodynamic calculating results showed that the driving force of formation of Cu-Sn-Ln IMC will be reduced by adding small amount of Sn, that is, the growth of Cu-Sn-Ln IMC will be delayed. Adding Li2O has a depressing effect of Ln is efficient only in a limited local mole fraction range. 0.16 at. % of Ln is the maximum value and 0.08 at. % of Ln is the best value.

EES. 10
STRESS MEASUREMENTS IN THE LAYERS OF THIN FILM GAS SENSORS. Sung-Ho Cho, Youngman Kim, Choongnam National Univ., Dept. of Metallurgical Engineering, Kwangju, KOREA.

The mechanical properties of thin film materials are known to be different from those of bulk materials, which are generally overlooked in practice. The difference in mechanical properties can hinder the estimation in the residual stress states in micro-gas sensor with multi-layer structure during manufacturing and in service. In this study the residual stress of each film layer in micro-gas sensor was measured according to the five difference sets of film stacking structure used for the sensor. The Pt thin film layer was found to have the highest tensile residual stress, which may affect the reliability of micro-gas sensor. For the Pt layer the changes in residual stress were measured as a function of processing variables and during thermal cycling. In addition the effect of heat treatment on the microstructure was investigated during processing of the sensor. The residual stresses in the Pt layers caused by microstructural changes were also investigated.

EES. 20

Laboratoire de Physique de la Matière, UMR CNRS 5513, INSA de Lyon, Villeurbanne, FRANCE

We report here on the influence of the epitaxial growth conditions on the residual stress of heteroepitaxial 3G-SiC, as an alternate material for MEMS, grown on silicon using APCVD and on the determination of its mechanical properties. 3G-SiC films were grown on [100] Si substrate in a vertical reactor by atmospheric-pressure chemical vapour deposition (APCVD). SiH4 and C2H4 are used as precursor gas and as carrier gas. The growth procedure involves the formation of a nitridation buffer layer at 1150°C under a mixture of NH3 and C2H4. The epitaxial growth occurs then at 1350°C by adding SiH4. The measurement techniques implemented are the substrate curvature, nano-indentation and load deflection measurements of self-assembled SiC membranes. The substrate curvature measurement leads to the determination of the residual stress in the deposited SiC film. We will show that we can achieve 3G-SiC layers with a compressive or a tensile state that is in a stress range from -550 MPa to 640 MPa. Whereas thermal mismatch just accounts for tensile stresses, we determine the possible stress relaxation compensation using specific conditions for the buffer layer formation. The early stage of growth is indeed of major importance. Regarding the mechanical properties, the 3G-SiC Young's modulus was determined using nano-indentation. Its mean value reaches 360 GPa comparable to the calculated value of 320 GPa. As test structures, we have processed self-assembled SiC membranes. Load deflection measurements enable to determine the Young's modulus and the residual stress of the self-assembled films. In self-assembled SiC membranes, the absolute value of the residual stress in the SiC thin films steadily decreases and is around 200 MPa in a tension state. This stress decrease is due to the stress relaxation in the thin films when the self-assembled membranes are etched.

EES. 21
DOUBLE SIDE POROUS SILICON ON PATTERNED SUBSTRATES FOR THERMAL EFFECT MEMS SYSTEMS. Stephanie Pecher, Volodymyr Lysenko, Boudjemaa Remaki, Daniel Barbier, INSA de Lyon, Materiais Physics Laboratory (LPM), Villeurbanne, FRANCE.

Application of porous silicon in thermal microsystem structures often requires the formation of deep localized porous silicon layers. The most commonly used method to prepare the porous layers is the dc anodization of monocrystalline silicon in a hydrofluoric acid based electrolyte. However, inhomogeneity of the nanostructures size along the layer depth due to the decrease of HF concentration within the pores as well as the poor uniformity of the porous layer thickness limit the elaboration of deep porous layers. Thus we proposed an original pulsed modulation technique, using a double task etching cell, that allows to make localized porous silicon layers through the whole wafer thickness. An alternate pulsed modulation current forms porous layers on each side of the silicon wafer. The duration of each pulse varies from 0.1 to a few seconds, the duty cycle (etching time/etching stop) from 0.1 to 1. Mono-porous silicon, 300 μm thick, was prepared on 0.025 cm silicon wafers and characterized in depth by micro-Raman spectroscopy. The pulse modulation reveals a progressive reduction of the crystal size along the layer depth. Furthermore a selective side modulation of silicon was performed on patterned silicon substrates. Porous silicon is formed in predetermine parts of the wafer using composite polysilicon - silicon nitride layers. Technological solutions to get rid of porous layer thickness inhomogeneity due to non uniform current density distribution are discussed. Finally a toric porous silicon layer, crossing the whole silicon wafer, surrounding a 2 mm diameter monocrystalline silicon cylinder was successfully achieved ensuring a new approach of thermal isolation for thermal effect microsystems.

EES. 22
ON THE ROLE OF THE UNDERLYING MICROSTRUCTURE ON THE OBSERVED MACROSCOPIC PROPERTIES OF MEMS MATERIALS. Guy F. Bruce, and Kevin J. Hemler, Johns Hopkins University, Dept. of Mechanical Engineering, Baltimore, MD. Visiting from LPM-CNRS, University Paris XIII, FRANCE.

The flourishing new technology of Micro-Electro-Mechanical Systems [MEMS] shows great promise in various areas, comprising for example critical applications such as weapons. Polycrystalline silicon thin films, a few microns in thickness, are the primary structural support materials for MEMS applications. Nevertheless, a better understanding of the correlation between mechanical properties and thin films microstructure is needed for reliability of MEMS devices. In earlier work [Sharpe et al., Youngs Modulus and Strength of Three Polysilicon, this symposium], the mechanical properties of polycrystalline silicon thin films supplied by Cronos (MCNC), Standard MEMS Inc. (SMI) and Sandia National Laboratories have been tensile tested using a special microsample testing setup. The strength of these films was found to be 1.6 GPa, 2.1 GPa and 2.2 GPa respectively. In the present work extensive Scanning Electron Microscopy, Atomic Force Microscopy and Transmission Electron Microscopy studies have been undertaken to characterize the underlying microstructure of CRONOS and SMI materials. Variations in sample geometry, surface roughness, grain size distribution and orientation will be quantified and compared to the differences in strength that have been reported. Special attention will be paid to processing-microstructure-property relations throughout the cooperation with D.A. Larson of Sandia National Laboratories and R. Mali of SMI in arranging supply of the specimens is gratefully acknowledged.

This research was conducted under the sponsorship of DARPA F30602-98-2-0558.

EES. 23

Electrodeposited LIGA Ni structures have received considerable attention in recent years because high aspect-ratio Si structures of these materials can easily be made with a high precision. The emergence of elevated temperature microelectromechanical systems (MEMS) applications has resulted in the need for an understanding of microstructural stability and high temperature mechanical properties of LIGA Ni. The doctor shaped LIGA samples used in the current study have been annealed at temperatures of 400°C to 800°C for 5min. to 6hours. Cross-sectional optical micrographs evidence a transition from the as-deposited columnar microstructure to more equiaxed grains at temperatures between 400-500°C after hour annealing. Extreme grain growth was observed above 500°C. The microhardness and tensile properties of the as-deposited and heat treated microsamples have been measured, and these results evidence a dramatic decrease in strength for specimens heat treated at temperature above 400°C. The evolution of the mechanical properties of the annealed microsamples will be combined with elevated temperature creep tests and used to develop an understanding of the elevated temperature mechanical properties relations that exist in LIGA Ni MEMS materials. The results of this study will also be confronted with an intermediate temperature application that is currently under development at NSWC.
EES 24
MECHANICAL PROPERTY CHANGES IN LPCVD DEPOSITED LOW-STRESS SILICON NITRIDE FILMS AS INFLUENCED BY STRESS TUNING OF DEPOSITION PARAMETERS.
Kevin R. Roberts, Gary A. Ozarow, Univ. of Minnesota, Microtechnology Lab., Minneapolis, MN; Jeremy Thurn, Yu-Te Tung, Robert Cook, Univ. of Minnesota, Dept. of Chemical Eng. & Materials, Minneapolis, MN.

A popular material in use today for surface micromachining is LPCVD (Low Pressure Chemical Vapor Deposited) low stress silicon nitride. This silicon nitride is deposited at temperatures of around 1000°C, pressures of 10 MPa or less, and temperatures of 350°C or less. Much work has been done outlining the effects of process parameters on the average wafer level film stress. To gain greater insight into the mechanical aspects of these films, additional properties were studied while tuning these films to a particular stress. Low stress silicon nitride films on the order of 1 micron thick were formed under varying LPCVD furnace conditions. Average film stress was measured before and after etching to determine changes in stress due to etching pressure, and gas composition ratio (Ammonia to Dichlorosilane ratio) for different etch techniques. These sample groups were representative of desirable low-stress silicon in MEMS applications (150 MPa compressive to 300 MPa tensile). In addition to the necessary determination of the average stress of these films, other mechanical properties of these films were determined and correlated to the process parameter used to adjust the stress. Additionally, in the case where the gas ratio was used to adjust the stress, the Si to N ratio of the samples was determined using X-ray Photoelectron Spectroscopy (XPS) and correlated to the property parameter change. The mechanical properties measured in these films were: modulus (including hardness), (including modulus), coefficient of expansion, and thermal stability. Understanding of the effects of deposition parameters on mechanical properties will lead to better control of these properties for advanced MEMS applications.

EES 25

Modern devices in the macroscopic world often combine components made from metal, plastics, and ceramics in order to attain improved performance and functionality. In contrast, microelectromechanical systems (MEMS) are fabricated mainly from silicon and a few metals, resulting in limited functionality. In order to increase the range of materials available for MEMS, our group has developed and combined different microfabrication and materials processing techniques. For instance, we have established a complete ILGA (laser based lithography) program to produce high aspect ratio metal micromolds or microstamps by electroplating. We commonly plate nickel, copper, nickel-iron, and gold. A combination of ILGA, polishing, and electroplating allows us to make three dimensional metal structures with micron size features on the internal surface. Such wafers have applications in micromachined resonant cavities and microbolometers for actuation. Using ILGA fabricated microstamps to produce plastic replicas by either hot embossing or injection molding. Plastic micromolds are desirable as enabling components of microfluidic and medical instrumentation. Ceramic or noncomposite micromolds, with useful range of thickness and temperatures determined to be 110°C toughness, were produced by micromolding ceramic nanoparticles into ILGA produced plastic molds. Finally, we have developed micro powder metallurgy techniques that allow us to make micromolds from a variety of materials including stainless steel. This talk will describe our baseline processing materials, technologies, and applications.

EES 26
FABRICATION OF NITIH HIGH-TEMPERATURE SHAPE MEMORY ALLOY THIN FILMS. X.L. Liang, H.S. Shen and Y.N. Wang, National Laboratory of Solid State Microstructures, Nanjing University, Nanjing, PR CHINA.

Shape memory alloys (SMAs) thin films are one of the candidate materials for Microelectromechanical System (MEMS). A lot work has been done on the fabrication and shape memory effect (SME) of SMAs thin films. However, most work focus on NiTi thin films, which transformation temperature are 372 K. This hinders its application in high temperature environments. So it is imperative to develop high-temperature SMAs thin films. As we know now, the transformation temperature of NiTi thin films can be enhanced by ternary substitution Hf or Pd for Ti or Ni. In this paper, we try to fabricate NITiH thin films by magnetron sputtering. The crystallization conditions of sputtered thin films are investigated and the martensitic structures of thin films are determined by XRD. The transformation temperatures are above 373 K. Shape memory effect has been observed and measured by bending experiments.

EES 27
UNSTABLE ETCHING OF SILICON(110) IN KOH. K. Morkadie, K. Sato, M. Shibata and T. Shizumu, Dept. of Microsystems Engineering, Nagoya University, Nagoya, JAPAN.

Nowadays, silicon microetching is a popular technique that is used to fabricate sensors and actuators. KOH and TMAH are the most common products used for etching and are known to be anisotropic. After etching, the smoothness of obtained surfaces is of crucial importance for the performance of the fabricated devices. It is therefore critical to study the mechanisms of the roughening and facetting of surfaces during silicon dissolution. Under specific experimental conditions, etching of Si(110) leads to the formation of hillocks with pyramidal shapes. These pyramids are often bounded by [111] vicinal planes and [100] ridges. For etched Si(110), the surface shows a hills and valley structure. The hills and valleys are formed along directions different from the etching direction. In the present work, we suggest an interpretation for the early stage formation of faceted surfaces. KOH. Silicon wafer oriented (110) were etched in KOH. The KOH concentration used is 30% and the etching temperature was 70°C. The surfaces were investigated using a laser scanning microscope (LSM) and a scanning electron microscope (SEM).

ZAYGO NEWSLETTER, May, 1999. Many studies show that the anisotropy of the surface tension is one of the causes of the faceting during crystal growth. Recently, A. Golovin and coworkers[4] have developed a phenomenological model for the formation of facets and corners in a thermodynamically unstable crystal surface (in the case of kinetically controlled growth). In their study, the faceting is caused by surface anisotropic etching. In certain conditions the surface structure shows grooves forming a quasi 1-dimensional pattern (oriented in x or y direction) for [110] crystallographic orientation of a crystal with cubic symmetry. We suggest that the early stage of formation of facets in Si(110) can be interpreted using the linearized version of the equation of Golovin et al. We performed a linear stability analysis to understand the origin of the faceting in Si(110) when etched with KOH. The linear theory predicts a large band of shear vectors in [110] direction that grow in time, leading to the formation of facets. The results show a dominant wave vector which maximizes the structure factor. The results are qualitatively reproduced by the theory. These results show that anisotropic surface tension is responsible for facet formation. 1. R.F. Sekerci, J. Cristal Growth 128, 1 (1998).

EES 28
Abstract Withdrawn.

EES 29
SIMPLE AND LOW COST PATTERNING PROCESS FOR SPATTERED Pt(Zr,Ti)Ox THIN FILMS AND ELECTRODES FOR MEMBRANE-BASED MICROSYSTEMS APPLICATIONS. Cyril Millon, Christophe Malherbe, Emmanuel Denoy, Daniel Barbec, Stephane Perichon, INSA, Lyon, France, Materials Physics Laboratory (LPM), Villeurbanne, FRANCE.

Microsized silicon membranes actuated by a piezoelectric thin film of great interest for microfluidic or ultrasonic applications. In this paper, we present a simple and low cost patterning process for sputtered Pt and TiOx films using lift-off and a wet HCl etching methods respectively. We have shown by simple element analysis the interest to pattern electrodes in order to get higher actuation performance. Moreover, in order to reduce the stress on the diaphragm, the PtZT film has been also patterned. We propose an optimized flow chart that takes into account the different material properties in the micropipet stack and the need of the PtZT crystalization annealing. To show the influence of the actuator layout, finite element models of a 20 μm thick, 3 x 3 mm2 silicon membrane with variable electrode design, actuated by a 1 μm PtZT (10V bias) thin film have been developed. We found a maximum deflection for a 1.7 mm side length square electrode located to the membrane center. Sputtering was achieved on a non heated silicon substrate, in pure Ar gas, using a stoichiometric PtZT target. The metallic PtZT electrodes have been structured by standard lift-off technique and bondpads have been located on the membrane frame to avoid stress effects. Different concentrations of HCl [4%,9%] with temperature up to 80°C have been tested. Well defined PtZT microstructures were better achieved by wet etching of non annealed PtZT film onto SiO2 or Pt (5%, 95°C). The etching rate was 0.07 μm per second. The presence of the pervoskite phase in the PtZT films for a 70°C, 30s, in air, HCl, has been checked by X-ray measurements. Finally, the silicon membranes have been actuated by piezoelectric chemical etching in an aqueous KOH (40%, 60°C) solution.
**EES.30**

MECHANICAL NANO-MACHINING FOR MEMS APPLICATIONS, Guochu Zhou, Yury Gogotsi, Drexel University, Department of Materials Engineering, Philadelphia, PA; Sang-Song Ku, Sabri Cetinkunt, University of Illinois at Chicago, Department of Mechanical Engineering, Chicago, IL.

The single point diamond turning (SPDT) machine was used to make grooves on (111) p-type single crystal silicon surfaces at room temperature. A diamond cutting tool of a high precision air bearing spindle and an X-Y stage plus a manipulator with about 2.5 nm resolution. Scratch tests have been performed with both a sharp diamond tool (Vickers or conical indenter) and a spherical diamond tool (Rockwell indenter). Material removal mechanisms appeared to be different for these tools. Pressure-induced metallization of Si allows for the ductile regime mechanical micro-manufacturing and surface finishing. Raman and electron microscopy were used to determine the machining regimes that do not introduce cracking or other damage. For example, grooves (channels) for microfluidic devices can be engraved with the channel shape determined by the shape of the tool, thus providing a possibility to create the structures that cannot be produced using etching. There is no limitation for the channel length/direction, and the channel width can be varied from nanometers to several microns. The surface of the groove after machining was covered by a mixture of metastable polymers of silicon or amorphous silicon. These phases can be transformed to cubic silicon by subsequent annealing. The maximum depth of cut in ductile regime has been determined for the given tool and cutting conditions. These results can be used for micro- and nanomanufacturing of Ge, GaN and other semiconductors.

**EES.31**

MICROFABRICATION OF CREVICE CORROSION SAMPLES, Xiaoyan Wang, Michael L. Reed, Robert G. Kelly, Jason S. Lee, Michael L. Reed, School of Engineering and Applied Science, University of Virginia, Charlottesville, VA.

A major challenge in developing computer models for crevice corrosion lies in fabricating appropriate experimental crevice samples. The geometry, dimensions, and materials of these samples must be controlled to a high order of precision in order to be comparable with computational models. In this work we report on efforts to construct crevice samples with rigorously defined dimensions by using microfabrication techniques developed for microelectromechanical systems (MEMS). These techniques include microfabrication with SU-8, electroplating, chemical mechanical polishing, as well as basic semiconductor device fabrication techniques. The crevice substrates contain two-dimensional arrays of electrodes of the metal to be studied, isolated by walls of SU-8. The electrodes have individual electrical connections so that spatial information of the in-situ corrosion process can be obtained. The crevice formers with SU-8 posts were coupled to crevice substrates to maintain a uniform crevice gap. Further, crevice formers with irregular substrates were fabricated to study the role of subcrevices in crevice corrosion.

**EES.32**


Fabrication of MEMS devices for applications in important areas such as optical communication, biotechnology, healthcare etc. requires transparent substrates compatible with conventional lithographic and micro-machining techniques. Ability to withstand high processing temperatures is crucial to fabricate a chip where the MEMS structure is integrated with a signal processing or driving electronic circuits. Novel transistor material at room temperature was the glass-ceramics recently developed by Corning Incorporation are suitable substrates for thin film polysilicon electronics and appear to be promising materials for MEMS processing. To explore the possibility of using these glass-ceramics as insulative substrates for MEMS fabrication and to investigate the effect of the structure and composition of the substrate on its etching behavior in the fluorocarbon plasma we processed wafers of LGA glass-ceramic, amorphous 'green' glass and amorphous fused silica. The LGA glass-ceramic consists of 10 nm spinel crystals evenly distributed in a siliceous glass matrix, while the "green" glass is amorphous and has the composition of LGA glass-ceramic. A 400 nm sputtered Cr film patterned by photolithography was used as an etching mask. Etching experiments were performed in a Materials Research Corp. Model 720 Magnetron Ion Etcher. SEM, AFM, Microprobe, XPS, TEM and EELS techniques were employed to analyze the effect of CF4 plasma on surface morphology of the substrates, composition and structure near the surface. Etch rates as high as 80 nm/min were achieved in the multi-component "green" glass and glass-ceramics, however this value is lower than that of pure fused silica. Although the etch rates of "green" glass and glass-ceramic were similar, planar etched amorphous "green glass" had a higher surface roughness than that of glass-ceramics. Changes in the surface composition and structure of the multi-component substrates will be discussed.

**EES.33**

FABRICATION OF MEMS COMPONENTS BASED ON ULTRACRYSTALLINE DIAMOND FILMS AND CHARACTERIZATION OF MECHANICAL PROPERTIES, A. Summet, Materials Science and Chemistry Divisions, Argonne National Laboratory, Argonne, IL; O. Auciello, Materials Science Division, Argonne National Laboratory, Argonne, IL; B. Kramer, D.M. Green, Materials Science and Chemistry Divisions, Argonne National Laboratory, Argonne, IL; D. Erway, Materials Engineering Department, University of Illinois-Chicago, IL; J. Tucek, Materials Science and Chemistry Division, Argonne National Laboratory, Argonne, IL; N. Molodov, D. Mancini, Experimental Facility Division, Argonne National Laboratory, Argonne, IL.

The mechanical, thermal, chemical, and tribological properties of diamond make it an ideal material for the fabrication of MEMS components. Cost-effective fabrication of these components will involve coating Si components with diamond or by producing MEMS components via etching or selective area deposition of diamond films. However, conventional CVD diamond deposition methods result in either a coarse-grained pure diamond structure that prevents high-resolution patterning, or in a fine-grained diamond film with a significant amount of intercrystalline nickel. At Argonne National Laboratory, we are able to produce planar ultracrystalline diamond (UNCD) films for the fabrication of MEMS components. UNCD is grown by microwave plasma CVD using CH4 or CH3I as plasma, resulting in films that have 3-5 nm grain size, are 10-20 times smoother than conventionally grown diamond films, and can have a brittle fracture strength similar to that of single crystal diamond. We used lithographic patterning, lift-off, and etching, in conjunction with the capability for growing UNCD on SiO2 to fabricate 3-D UNCD-MEMS cantilevers and pinwheels. We also coated Si posts with conformal UNCD films to produce shafts for rotor and gear support. We have performed initial characterization of mechanical properties by using micromachined test structures. The values of Hardness (~88 GPa) and Young modulus (~860 GPa) measured are very close to those of single crystal diamond (100 GPa and 950 GPa respectively). The results show that UNCD is a promising material for future high performance MEMS devices.


**EES.34**

ASYMMETRICAL POLYSILICON ELECTROTHERMAL ACTUATORS FOR ACHIEVING LARGE IN-PLANE MECHANICAL FORCES AND DEFORMATIONS, Edward S. Kolb, University of Rochester, Ko, Jeffrey T. Han, University of Rochester, M. Wilken, Noah C. Boydston, Matthew D. Ruff and Richard J. Wilks, Texas Christian University, Department of Engineering, Fort Worth, TX.

Several 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. This investigation reports a new polysilicon electothermal actuator design. In the traditional electothermal actuator design, the single-hot arm is narrower than the cold arm, and thus, the electrical resistance of the hot arm is greater. When electrical current passes through the device (both the hot and cold arms), the hot arm is heated to a higher temperature than the cold arm. This temperature differential causes the hot arm to expand along its length, thus forcing the tip of the device to rotate about a flexure. The new double-hot arm thermal actuator design eliminates the parasitic electrical resistance of the cold arm by incorporating an additional hot arm. The second hot arm results in an improvement in electromechanical efficiency by providing a return current conductor that is also mechanically active. Furthermore, in the new electothermal actuator design, the rotating cold arm can have a narrower flexure compared to the flexure in the traditional device because it no longer needs to conduct an electrical current. These thinner flexures result in an improvement of electromechanical efficiency. This research compares the performance of the single- and double-hot arm electothermal actuator designs. Force and deflection measurements of both actuator designs as a function of arm length and applied electrical power are presented. The electothermal actuator designs were accomplished with the L-Edit software program, and they were fabricated using the Multi-User Microelectromechanical Systems (MEMS) Process (MUMPs) foundry at the Microelectronics Center of North Carolina (MCNC).
EES.35
ISSUES IN THE FLEXIBLE INTEGRATION OF SPITTER-DEPOSITED PZT THIN FILMS WITH POLY SILICON AND Ti/Pt ELECTRODES FOR USE AS SENSORS AND ACTUATORS IN MICROELECTROMECHANICAL SYSTEMS (MEMS).
C.F. Kuleshberg, T. Sando, Department of Materials Science & Engineering, University of California, Berkeley, CA, A.S. Nickles, Capacitor Division, Applied Materials, San Jose, CA. M. White, Department of Electrical Engineering & Computer Sciences, University of California, Berkeley, CA.

Sputter-deposited piezoelectric lead zirconate titanate (PZT) thin films with Ti/Pt and poly-silicon electrode layers are being investigated for use in Microelectromechanical Systems (MEMS). Existing research on the nucleation of the perovskite phase of the PZT is linked to the lattice spacing of the underlying Pt electrode and/or seed layers, and is key in obtaining PZT layers with good piezoelectric/ferroelectric properties. Our research with piezoelectric PZT films on Ti/Pt electrode layers aims at understanding acoustic wave generation and receive acoustic waves in flexural plate wave devices (FPWs). Our experiments indicate the formation of a random polycrystalline perovskite phase is linked to the emergence of oriented <200> Pz grains within the dominant <111>, oriented crystal structure during rapid thermal annealing in an oxygen environment. Pt films annealed in nitrogen, in contrast, retained their <111> preferential orientation without the formation of Pt <200> grains. PZT films deposited on these electrodes and annealed in nitrogen were strongly oriented in the <111> direction, but exhibited loamy ferroelectric behavior and were prone to delamination. We are also investigating the feasibility of using doped polysilicon electrode layers with PZT films. The multiple layers used with the Pt electrode (Pt, Ti, and silicon dioxide adhesion layer) have significant interactions with one another, and replacing these layers with a single electrode layer (which is the case in the FPW devices) is a low-temperature PZT deposition process and short annealing cycle (30 sec) coupled with a titanium dioxide barrier/seed layer should prevent interdiffusion reactions and between the polysilicon and piezoelectric PZT layers. Our experiments show PZT films deposited and annealed on doped polysilicon layers develop a random polycrystalline perovskite phase, but are subject to tensile cracking. The use of polysilicon as an electrode layer should also facilitate the integration of piezoelectric PZT layers with polysilicon surface micro-machined structures using SiGe sacrificial layers.

EES.36
FABRICATING STRESS COMPENSATED, PLANAR, SUSPENDED PIEZOELECTRIC THIN FILM BEAM RESONATORS.

Residual stress plays an important role in the fabrication of suspended thin film piezoelectric devices. A stress-dependent role of materials in a suspended dielectric / Ta / Pt / PZT / hafnium layer stack. PECVD SiO2, Si3N4, and combinations of both were studied as the dielectric. Residual stress measurements via wafer curvature and X-ray diffraction of all the films investigated were conducted. The Pt layers possessed the largest values with the bottom Ta / Pt layer (859 ± 29.1 Mpa) having a greater stress than the top Pt (50.6 ± 0.04 Mpa) depending on annealing conditions. In contrast, relatively low stress low tensile stress were present in the PZT (17 ± 18 Mpa) and SiO2 (88.8 ± 7.2 Mpa) layers. This stress gradient resulted in non-planar suspended beams in initial devices. The large residual stress of the bottom platinum layer caused the beams to bend about the neutral axis. To produce planar resonators, these large tensile stress were compensated through the use of additional dielectric layers e.g., SiO2, Si3N4, HfO2, and combinations thereof to stress balance the beams around the neutral axis. The relatively low stress SiO2 layers of thickness <1100 A caused a strain 

EES.37
MEASUREMENT OF ELECTRIC CHARGE DURING NANOINDENTATION EXPERIMENTS ON FERROELECTRIC THIN FILMS.
Miguel Alguero, Andrew J. Bushby and Michael J. Reece, Department of Materials, Queen Mary and Westfield College, University of London, UNITED KINGDOM.

We have developed a procedure using nanoindentation with spherical tipped indenters capable of providing the elastic modulus of ferroelectric thin films for MEMS devices that allows for their mechanical deformation under indentation. The procedure also provides the elastic and piezoelectric properties, and the contribution to the deformation as a function of the indentation stress. The procedure was demonstrated on a range of poled lanthanum modified lead titanate (Pb,La)TiO3 thin films. It was shown that the elastic modulus of the films ranged from 1.6 ± 0.2 GPa depending on the microstructure and orientation of the films. It was also shown that the anelastic deformation was associated with the movement of ferroelastic domain walls. An experimental method has been developed so that electric fields can be applied and the electric field generated can be measured during nonindentation. We present here results on the simultaneous measurement of penetration and electric charge generated during the indentation of poled (Pb,La)TiO3 films. The possibility of measuring an indentation piezoelectric coefficient with high spatial resolution is discussed.

EES.38
PROCESS AND FABRICATION DEVELOPMENT OF A PZT MEMS MAGNETOMETER.

The overall program goal is to develop an extremely sensitive microelectromechanical (MEMS) magnetometer, based on a resonating xylograph line structure. A preliminary prototype device for process development rather than operational performance has been completed. The structure was fabricated using sol-gel deposited PZT (Lead Zirconate Titanate - 52/48) onto a Pt/SiO2/Si substrate, with the Pt layer forming the bottom electrode. A subsequent Pt layer deposited onto the PZT formed the device top electrode. The resultant Pt/PZT/Pt/SiO2/Si stack was patterned with photolithography and defined by ion beam milling, and reactive ion etching. The SiO2/parylene-B sacrificial layer structure was used for PECVD SiO2 isolation film was deposited over the electrode contact areas, and then etched, followed by the formation of Ti/Au contact bonding pads using the latter technique. A Pt/Pt deposition line was then refilled. Measurements of residual stress in PZT/Pt/Pt films were also studied using a commercial stress analyzer.

EES.39
WET ETCH PATTERNING OF LEAD ZIRCONATE TITANATE (PZT) THICK FILMS FOR MICROELECTROMECHANICAL SYSTEMS (MEMS) APPLICATIONS.
Li-Peng Wang, S. Trollein-McKinstry and R.J. Dine, Penn State University, PA.

Lead Zirconate Titanate (PZT) films are very attractive for use in Microelectromechanical Systems (MEMS) applications because of their high piezoelectric coefficients and good electromechanical coupling. In this work, wet-etch patterning of sol-gel Lead Zirconate Titanate (PZT) films for MEMS applications, typically having films thickness ranging from 2 to 10 microns, was studied. A two-step wet-etch process was developed. In the first step, 10.1 buffered HF was used to remove the majority of the film at room temperature. Then, a solution of 2HCl:H2O at 45°C was used to remove residue from the first step. This enables successful patterning of PZT films up to 20 microns thick. The high etch rate (0.133 μm/min), extreme selectivity with respect to photosresist, and limited undercutting (2:1 lateral:thickness) were obtained. X-ray diffraction and scanning electron microscopy (SEM) were used to analyze the residue produced in the first etching step and examine the etch process properly. In addition, two MEMS devices, an ultrasonic transducer and an accelerometer, were demonstrated using this etching process to pattern the active PZT films.

EES.40
NONLITHOGRAPHIC DIRECT-WRITING AND LASER PROCESSING OF DIELECTRIC AND PIEZOELECTRIC STRUCTURES FOR MEMS APPLICATIONS.

The recently-developed MAPLE-DW deposition technique utilizes a focused, pulsed UV laser (355 nm) to transfer material from a transparent carrier onto a target substrate. In MAPLE-DW, the laser pulse propagates through the transparent layer and a continuous material that consists of the material to be transferred and an organic vehicle. The focused laser pulse decomposes the vehicle and propels the material from the carrier onto the substrate. This system is capable of concurrent in-situ laser machining, trimming, and thermal processing. The flexible combination of additive and subtractive capabilities allows direct-writing of 10 micron resolution structures. MAPLE-DW has been designed to operate in air, at room temperature, and without the need for special equipment or Etching. MAPLE-DW has been used to fabricate capacitor structures of barium titanate (BTO) and barium strontium titanate (BST) for dielectric applications. Similar lead zirconate titanate (PZT) structures were also produced for evaluation as piezoelectric actuators and sensors elements. The starting materials consist of an organic...
vehicle, dielectric powder, and metallographic precursor. Low temperature processing (400°C) of ITO and BST results in an adherent, optically transparent, porous material with dielectric constants of 75-100 and 150-200, respectively. In-situ processing with an IR annealing laser (1.064 or 10 microns) substantially improves both dielectric constant and low tangent, and alters the piezoelectric properties of BST. Dielectric measurements were performed as a function of frequency up to 1.5 GHz, and as a function of temperature from -130 to 150 Celsius.

**EEE.41**


Piezoelectric thin films on bulk micromachined silicon cavities are shown to respond electrically to a cyclic pressure wave. Two materials have been tested for use in power generation, a ceramic thin film (PZT) and a polymer thin film (PVDF) using solution deposition and thermal bonding respectively. The relationship between the deflection of the membrane and the resulting charge development were found using a dynamic balance test. The frequency response of both materials has been characterized, and is found to have a optimal pressurization frequency for power generation. The charge development during pressurization can be used to directly determine the dielectric constant of both piezoelectric materials. A variation in ceramic film processing utilizing a multilayer structure of alternating dopants (PLZT) with PZT has been shown to produce ferroelectric fatigue resistance of over 1 billion cycles. The ferroelectric film is compared to the power generation degradation during mechanical fatigue testing, and differences between the damped ferroelectric fatigue test and the flexing membrane of the direct mechanical test are discussed.

**SESSION EEE.5: PACKAGING**

Chair: M. Okandon

Tuesday Morning, November 28, 2000

Room 206 (Hynes)

**8:30 AM EEE.1**


The Digital Micromirror Device® (DMG) is a MEMS spatial light modulator that forms the basis of projection displays used in business, commercial, and home entertainment settings. With any MEMS device, packaging presents its own challenges, many of which are not standard MEMS packaging issues. The constraints presented by the nature and application of the device require special attention to many aspects of assembly and test. This talk will cover the evolution of the DMG® package, back-end processes, and testing, the importance of materials science and analysis on the path to an understanding of the package impact on device performance, as well as effective, lower cost packaging will be discussed.

**9:00 AM EEE.2**

**STRESSY METAL MEMS.** David K. Eich. Xerox Palo Alto Research Center, CA.

We report on a new type of micro-fabricated structure based on stress engineered metal thin films. Metals afford many enhanced properties compared to the conventional materials commonly used for fabricating micro-mechanical components. These properties include conductivity, hardness and intrinsic stress. DC magnetron sputtering is an effective technique for controlling the stress profile in a broad class of deposited materials. This has enabled the fabrication of micro-machined metal cantilevers that bow away from the substrate upon their release from the substrate. Useful application of this property is currently under investigation for flip-chip integrated circuit packaging and reusable spring contacts for circuit probing. The arrival of this technology may be timely given that bonding gap densities on high-performance integrated-circuit chips are beginning to exceed the limits of available interconnect technologies. We have micro-photographically fabricated functional off-chip interconnects from highly elastic cantilever springs in linear arrays on pitches down to 6 μm. The very high compliance of the springs may permit the fabrication of packages that are highly resistant to thermal fatigue. This work is performed in collaboration with Georgia Tech, and NanoNex Inc.

This work is supported in part by the NIST Advanced Technology Program under Award 70NANBH4008.

**9:15 AM EEE.3**


The increased number of MEMS devices that are fabricated by bonding two or more bulk micromachined silicon wafers has highlighted the need to produce silicon fusion bonds of high quality. Silicon fusion bonds are fabricated by bringing two mirror polished silicon wafers into contact and then subsequently annealing. It is of great interest to characterize the influence of various processing conditions on bond quality. In particular, there is a desire to reduce the annealing temperature because of the limitations it places on fabrication steps prior to bonding. In the current study, the annealing temperature and time as well as the contacting ambient and pressure were systematically varied among samples. The critical strain energy release rate, Gc, was chosen as the figure of merit by which to evaluate the bond quality. To measure the critical strain energy release rate, a four-point bend specimen composed of two bonded layers and an initial notch at the center was employed. This specimen geometry is advantageous because it does not require measurement of crack length to calculate the critical strain energy release rate and it is insensitive to damage near the specimen edges. The specimens were fabricated by bonding two silicon wafers and disassembling into individual specimens. To ensure that the crack propagated along the bonded interface, shallow trenches were etched in the surface of the wafers to reduce the area of the bonded region. This technique has proven to be repeatable and straightforward. Details of the test method and results will be presented.

**9:30 AM EEE.4**

**PHENOMENOLOGICAL MODEL OF NON-EVAPORATED GETTER FOR MICROMECHANICAL SYSTEMS (MEMS) APPLICATIONS.** Caroline A. Kondoleon and Thomas Marinis. The Charles Stark Draper Laboratory, Electronics Packaging and Prototyping Division, Cambridge, MA.

There has been increasing interest in the development and use of micro-electromechanical systems (MEMS) for various applications. Some MEMS devices such as gyroscopes, accelerometers and backbones, must be sealed under vacuum, at pressures below 10 microns, for efficient operation. A gas absorbing material (getter) is placed in the packages of these devices, to help maintain vacuum levels over service life of many years. Getter, of this type, is activated by heating under vacuum, just prior to sealing the package. This study was undertaken to develop a model that could be used to estimate the quantity of getter needed as well as optimize the activation process subject to process constraints on time and temperature. The material studied was a titanium and zirconium-based alloy (73 by weight) non-evaporable getter in the form of strips produced by SAES Getters. The zirconium alloy contains 60% (24.6%) and iron (5.4%) by weight. The getter was analyzed under different ambient conditions of temperature, time, and cyclic pressure. Auger Electron Spectroscopy (AES) depth profiling was used to analyze the diffusion depth of the contaminant gases absorbed by the getter material under each condition. The data acquired from the depth profiles were fit to a simple diffusion model. This model is currently being validated, by activating getter material under various ambient conditions, and measuring pressures and gas compositions inside packages using a residual gas analyzer (RGA). The utility of this model for optimization of getter activation and estimating package vacuum levels over time will be discussed.

**9:45 AM EEE.5**


High power density microsystems offer the potential to revolutionize technologies for portable electrical power generation, propulsion and flow control. Devices are being designed and fabricated which include micro-gas turbine engines, micro-rocket engines, micro-motor-compressors, micro-pumps and micro-hydraulic transducers. Common to all of this family of devices is the need for a high power density microsystem that service the devices, and interface them with the macroscale environment. Fluid interconnections are a particularly demanding packaging element for this class of devices. In order to achieve high power densities, these devices are required to operate at high pressures and, in some cases, high temperatures. This paper will describe the design, analysis, fabrication and testing of high pressure, high temperature fluid connections for the microsystems and micro-rocket applications. A glass bonding technology has been developed to allow the creation of multiple fluidic connections.
SESSION EE7: NEW MATERIALS
Chair: Hal Karp
Tuesday Morning, November 28, 2000
Room 206 (Hynes)

10:30 AM *EE7.1

Silicon is often the MEMS material of choice due, in large part, to the extensive infrastructure developed to support this material. In many instances, alternative materials, such as glass and silicon, are not commonly encountered with one new surfer micro-machined MEMS material, amorphous diamond (a-D). This material possesses many advantages over silicon, including a naturally hydrophobic surface that resists oxidation, excellent wear resistance, chemical inertness, and high fracture strength (> 8 GPa), and bio-compatibility (e.g., for bioMEMS). In addition, the material possesses a two-phase microstructure (a nanophase mixture of 4-fold and 3-fold coordinated carbon) that permits a host of exotic properties, such as plastic-like deformability while maintaining an ultra-high elastic modulus, > 700 GPa. It is not affected by high temperature, and wettability is excellent. Silicon is not affected by the deposition process, which is carried out within a room-temperature ambient. The deposited material, a diamond, is extremely hard and wear resistant. The a-D material is extremely hard and wear resistant.

A wide array of materials have been investigated as candidate fabrication templates for precision microelectromechanical structures, including boron-diffused silicon, boron-doped epitaxial silicon, polysilicon, silicon-on-insulator, and wafer-thick bulk structures. Here we present the latest fabrication results for epitaxial silicon-germanium alloys, a new class of materials which possess excellent crystalline structure, are compatible with non-toxic etchants in bulk micromachining, and are capable of on-chip integration with electronics. For MEMS applications, silicon-germanium alloy layers are grown using a graded buffer approach, resulting in very high quality micromachined structures. Very low defect densities are obtained through the use of these relaxed buffers. Original etch-stop studies determined that Ge doping provided a very weak selectivity in anisotropic etchants such as KOH and EDP. However, by extending the range of Ge concentration to over 20%, we have found extremely high etch selectivities in a variety of etchants. Unlike boron-doped layers, SiGe exhibits etch-stop characteristics in the non-toxic, process-compatible solution TMH. The combination of independence from boron doping concentration and etchant compatibility makes SiGe a material that is ideal for integration with on-chip electronics. In this work, we present the latest fabrication data on diamond-like a-D micromachined structures built using SiGe epitaxial layers. Process compatibility issues related to wafer curvature, surface finish and reactive-ion-etching chemistries are addressed. An unexpected result of the fabrication process, a transition of released structures in a linear fashion, is also reported after the SiGe deposition. Changes in Young's modulus arising from the high fraction of Ge in the device can be determined by simple beam analysis based on observed resonant frequencies. The quality factor of the motor drive resonator is determined by optical spectroscopy of the gyroscope in vacuum. Overall, build precision for these devices is excellent. We conclude by addressing the remaining challenges for wide-scale implementation of silicon-germanium epitaxial MEMS.

SESSION EE8: OPTICAL MICROSYSTEMS AND PROCESSING TECHNIQUES
Chair: Arturo A. Ayres
Tuesday Afternoon, November 28, 2000
Room 206 (Hynes)

1:30 PM *EE8.1
MECHANICAL OPTICAL MICROSYSTEMS. Paul V. Lambeck, MESA Research Inst., Univ. of Twente, Enschede, THE NETHERLANDS.

Monolithic integration of integrated optical and micromechanical subsystems offers the prospect of small robust microsystems with a large number of functionalities. On the one hand the integrated optical part can be used for the read-out of the position and also of the movement of micromechanical components such as membranes and cantilevers. On the other the mechanical sub-system is used for the properties of the integrated optical sub-system as applied e.g. in switching matrices for the optical telecommunications. Several principles used in these mechano-optical MOEMS systems will be highlighted. The monolithic integration requires the compatibility of the technologies needed for realizing the micromechanical and optical part and this sets limits to the materials, that can be applied within these systems. A promising approach is to fabricate in a first step both individual sub-systems and to bond them together in a second step. This can be well done e.g. by aligned waferbonding, if both the micromechanical and the integrated optical sub-system are made by Silicon-based technologies, the optical part e.g. being realized by a (doped) Silicon nitride technology or a Silicon monolith technology. Special attention will be paid to the latter technology and to the additional steps needed for combining both sub-systems. Some monolithically integrated opto-mechanical systems will be treated.

2:00 PM EE8.2
RAPID PHOTOTYPING OF IMICROMAGNETIC SYSTEMS FOR MANIPULATION OF MAGNETIC BEADS. Tho Deng, George M. Whitesides, Harvard Univ., Dept. of Chemistry and Chemical Biology, Cambridge, MA; Gary Zolot, Mina Rudolph, Abay Ahmed, Harvard Univ., Dept. of Physics, Cambridge, MA.
Current-carrying circuits fabricated using soft lithography are used to create strong magnetic field gradients for controlling the position and/or velocity of paramagnetic microbeads in aqueous suspension. Such paramagnetic beads are widely used to manipulate or sort biological material that can be selectively attached to the surface of the beads. We show that the beads can be captured from solution, held in a fixed position, and released at will. We also show that the beads can be moved along complicated paths and that simply changing the current flowing in the circuits can dynamically reconfigure the field. The selective capture, transport, and confinement of magnetic beads using microfabricated circuits should expand current sample handling capabilities, and can be used with or without the presence of net fluid flow and microfluidic channels.

2:15 PM EEE.3
A ROBUST CO-SPUTTERING FABRICATION PROCEDURE FOR TiN/SHAPED MEMORY ALLOYS FOR MEMS, B.K. Lu1, H. Kahn2, G. Hahn2, I. You2, S. Phillips2 and A.H. Heuer2, 1Dept of MS&E, 2Dept of Electrical Engineering and Computer Science, Case Western Reserve University, Cleveland, OH.

Co-Sputtering has been used to fabricate equiatomic thin films of TiNi, a shape memory alloy, which form the basis of microactuators with many applications in MEMS. The difficulties involved in obtaining equiatomic TiNi thin films with high transformation temperatures, and a robust procedure suitable for batch fabrication in a production environment, will be described. The performance of the TiNi actuators has been characterized, with regards to actuation force, recovery strain, switching speed, and fatigue resistance. The performance of microfluidic devices using these actuators will also be presented.

2:30 PM EEE.4
PROCESSING OF THICK DIELECTRIC FILMS FOR POWER MEMS: STRESS AND FRACTURE. Kuo-Shen Chen, National Cheng-Kung University, Tainan, TAIWAN; Xin Zhang, Massachusetts Institute of Technology, Cambridge, MA; Ren Gao, University of Maryland, College Park, MA; S. Mark Spiegler, Massachusetts Institute of Technology, Cambridge, MA.

Thick dielectric films for high power MEMS-based devices are required in order to reduce capacitive loading and enhance surface charge density. However, such thick deposited layers often result in severely bowed wafers while deleterious effects of residual stress impose major restrictions on the device performance. The present work is focused on the characterization of residual stress and modeling of fracture behavior of dielectric films. 1630 microns silicon or tetramethylsilane (TEOS) based PECVD oxide films were deposited using a Noyes™ Concept One System. To counteract the high compressive stress inherent to the oxide film, a thin layer (less than 1 micron) of highly tensile silicon nitride film was deposited by LPCVD, either prior to deposition of the oxide film, or after the thick oxide deposition. The residual stress between the two oxide layers was found to be influenced by the stress component. Fracture toughness of nitride films was measured using a microindentation system while scratch resistance was measured using a nanoindentation system. Surface composition of oxide films was examined using SIMS and RBS. Dissolved gasses were found to play an important role in governing intrinsic stress. Both diffusion-reaction and constrained sintering models were constructed to characterize the bulk transformation stresses and the growth of intrinsic stress in the films. Fracture mechanics was applied to analyze the crack growth and propagation in the thick dielectric films and the critical temperature (or critical film thickness) needed to avoid cracking was further predicted. Finally, optimized dielectric films were fabricated which exhibited less and even zero wafer bow for a specific combination of film thickness.

2:45 PM EEE.5
MICROBONDING TESTING OF SILICON OXIDE/SILICON NITRIDE BILAYER. Cai Fu Qian, Yan-Jing Su, Ming-Ho Zhao and Tong-Yi Zhang, Department of Mechanical Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, CHINA.

The present work further develops the microbond testing method to characterize mechanical properties of thin silicon nitride films. We modeled the substrate deformation with three coupled springs and consider residual stress in each layer to formulate deflection versus load under large deformation, resulting in a closed-form formula. If the mechanical properties of one layer are known, and the closed-form formula is able to simultaneously evaluate the Young's modulus and residual stress of the other layer and the bending strength of the bilayer films from the microbond test. The analytic results are confirmed by finite element calculations. Using a loosely constrained microsensor system equipped with a microwire probe, we conduct microbond tests on low-temperature silicon oxide/silicon nitride bilayer prepared by the micromechanical technique. The experimental results verify the proposed method. The results show that for small deformation, the load-deflection relationship is approximately linear. Under large deformation, bridge deflection couples with the neutral plane stresses such that both the tensile-equivalent and compressive equivalent Young's modulus are involved. Under small deformation, one may use the bending-equivalent Young's modulus and the residual stress, or the tensile-equivalent residual stress to reduce the bilayer to a problem with two homogeneous layers. For some substances, the substrate deformation plays a very important role in extraction of the elastic constant and the residual stress from the microbond test under either large or small deformation. Supported by the Hong Kong Research Grants Council.

SESSION EEO: PROCESSING TECHNIQUES II
Chair: Carol Livermore
Tuesday Afternoon, November 28, 2000
Room 206 (Hynes)

3:30 PM * EEO.1
UNDERSTANDING AND CONTROLLING WET CHEMICAL ETCHING OF SILICON. M. Elezropek1, W.J.P. van Endew2, J.G.E. Gardeniers1, A.J. Nijhuis1, J. van Sachtelen1, E. van Veenendaal2, E. Vlieg3, 1University of Twente, MESA Institute, Enschede, THE NETHERLANDS, 2University of Nijmegen, Nijmegen, THE NETHERLANDS.

In this paper we review the progress that has been made during the past 30 years to understand the physical and chemical processes which underlie wet chemical etching of single crystals, in particular silicon. The etch rate of single crystalline silicon depends strongly on the crystallographic orientation in certain etching solutions (such as aqueous KOH solutions, hydrazine) with a deep etch rate minimum in the (111)_a direction. It is now well established that the minimum is due to the fact that the (111) plane of silicon etches via a step mechanism: atoms are removed at edges of steps of a height of one or more atoms or more which are abundant on (111) faces with a slight misorientation. New steps must nucleate on perfectly oriented (111) faces. From the chemical point of view the most important insight was that the (111) is hydrogenated during etching in KOH, and that as the rest potential the number of electrons exchanged during etching is very small chemical etching dominates. It is thought now that the water molecule reacts with silicon, the hydroxyl ion being a catalyst. Once having accepted this basic fact, a great number of phenomena can be understood. We summarize a few; (i) Steps can only exist on faces below the roughening transition. Monte Carlo simulations showed indeed that a crystal face steps rough on an atomic scale even at infinitely large underetching - which is thought to be equivalent to the roughening transition. The (111) being so strong and etches fast, although each atom in the flat face has three back bonds. (ii) New steps on the (111) face must nucleate. Nucleation centers seem to be the outgrowth of edge dislocations. Since edge dislocations grow themselves nucleated as oxide precipitates by thermal treatment, (111) faces appear rougher (on a microscopic scale), showing cracks centered around edge dislocations. This has consequences of technological relevance: the crystal front adjacent to main silicon steeps itself. (iii) Nucleation of steps was enhanced at the interface between a mask and the crystalline material. Measuring etch rate and its anisotropy using a wavy mask pattern may give misleading results: (iv) Hillocks of pyramidal form and roof like structures which nucleate under circumstances on (100) and (110) oriented surfaces, respectively, can be understood by the step flow together with a mechanism which hinders the etching of the atoms at the tip of the structures. (v) Step flow allows us to calculate the etch rate as a function of the orientation using physically transparent parameters which, in principle, can be determined independently.

4:00 PM EEO.2
LOW TEMPERATURE Si DIRECT BONDING BY PLASMA ACTIVATION FOR FABRICATION OF MEMS DEVICES. Y sanit Cho, Department of Materials Science and Engineering, University of California, Berkeley, Berkeley, CA; Nathan W. Cheung, Department of Electrical Engineering and Computer Science, University of California, Berkeley, Berkeley, CA.

Waferscale Si direct bonding is a critical process in the fabrication of
cavities, microchannels and multi-level microstructures commonly used in MEMS applications. Direct bonding eliminates the need for the application of intermediate layers and external forces such as electric fields used inodic bonding. When done at a low temperature, Si direct bonding can further place itself as the most robust and device-compatible bonding process for MEMS applications. However, the first reported Si direct bonding by Limd [1] and Shimbo et al. [2] required post-bonding thermal annealing above 1000°C due to initially weak room temperature bonding. The first single crystal Si resonant pressure sensors demonstrated by Peterson [3], also utilized high-temperature Si fusion bonding. High temperature bonding or annealing is detrimental to today’s microsystems in terms of thermal mismatch and electrical degradation in metallized device structures. Recently, chemical and dry surface activation methods have been demonstrated. In this paper, plasma activated low-temperature Si direct bonding is presented. Dramatic improvement of bonding strength after exposure to oxygen plasma is measured by a crack opening method [4]. Post-bonding annealing as low as ~100°C was sufficient to achieve full bonding strength. Bonding activation energy is investigated and surface chemical analysis is utilized to study the enhanced bonding phenomenon.

References:

4:15 P.M. E09.3
MEMS MATERIALS AND FABRICATION TECHNOLOGY FOR LARGE AREAS: THE EXAMPLE OF AN X-RAY IMAGER
Jurgen H. Daniel, Brent Kruer, Marcelo Morato, Rui Apte, Robert A. Street, Xerox Palo Alto Research Center, Palo Alto, CA; Adela Greceda, Peter M. Kozumpraw, Xerox Research Center Canada, Mississauga, Ontario, CANADA

Microfabrication has potential applications for large area image sensors and displays, but conventional MEMS technology based on crystalline silicon wafers cannot be used. Instead, large area devices are deposited or patterned on glass substrates. This presents many challenges for MEMS, both in regards to materials for micro-machined structures and the integration with large area electronic devices. We are exploring the novel thick photoresist SU-8, as well as plating techniques for the fabrication of large area MEMS. As an example of our application, we have applied this thick MEMS technology to improve the performance of an amorphous silicon based image sensor array. SU-8 is explored as the structural material for the X-ray conversion screen and as a thick interlayer dielectric for the thin film readout electronics of the imager. Medical X-ray imagers have a thick (200-500 microns) layer of phosphor, which converts the X-rays into visible light, placed directly on top of the photodiodes. Spiral resolution is limited because of light scattering in the phosphor. In order to obtain the full resolution of the pixel array, the phosphor layer needs to be micro-patterned into cells which collimate the generated light. This cell structure was patterned with a 300-400 micron thick layer of SU-8. The SU-8 cell walls need to be made reflective in order to present light from scattering into a neighboring cell which is achieved by sputtering a thin metal layer. Subsequently the cells are filled, in a phosphor. A second application is the use of SU-8 as a thick interlayer dielectric to reduce noise due to capacitive coupling in the thin film electronic circuit of the imager. Nickel electroplating is used to metallize the deep contact vana. The compatibility of SU-8 with thin film deposition methods, such as amorphous silicon PECVD, will be discussed. Processing challenges which are particularly important for large area fabrication, will be addressed.

4:30 P.M. E09.4
MICROFABRICATION OF CERAMICS ON SUBSTRATES TOWARDS HIGH-SENSORS APPLICATIONS
M. Heile, L. Meier, L.J. Gaukler, ETH Zurich, Dept. of Materials, Zurich, SWITZERLAND.

Many research efforts are made to widen the range of materials in the fabrication of microelectromechanical systems (MEMS). Ceramic powders in gas sensor fabrication facilitate the use of a wide range of complex oxide compositions compared to gas phase processes such as chemical VCD and physical vapour deposition (PVD). Moisture-free, fine ceramic powders are successfully applied in Micro Electro Mechanical System (MEMS) using sintering techniques. The retained feature size strongly depends on the powder size but on the preparation of the colloidal suspension as well. We applied these techniques to produce ceramic micro-lines of tin oxide. Using 0.25 micron oxide powder, structures of 10 microns were well reproduced. A method to apply electric wiring to micro-structured ceramic parts was developed in order to get a functional device. Our sensors cover an area of only 8x80 square-microns including 4-point probe platinum circuit lines. Sensor responses to hydrogen gas concentrations of a few ppm were recorded.

4:45 P.M. E09.5
THE MECHANICAL PROPERTIES OF POLYCRYSTALLINE SILICON CARBIDE FILMS DETERMINED USING BULK MICRO-MACHINED DIAPHRAGMS
Shave Roy, The Cleveland Clinic Foundation, Department of Biomedical Engineering, Cleveland, OH; Christian A. Zerini, Mehran Behzargray, Case Western Reserve University, Department of Electrical Engineering and Applied Physics, Cleveland, OH.

Polysilicon is a dominant material in the fabrication of micro-electromechanical systems (MEMS); however, its mechanical properties begin to degrade at elevated temperatures (~350°C), making it increasingly unsuitable for high-temperature applications. In contrast, SiC is well known for its mechanical hardness, chemical inertness, high thermal conductivity, and electrical stability at temperatures well above 600°C. These properties make SiC an attractive alternative for MEMS in harsh environments; yet relatively little is known about its thin film mechanical properties. This paper presents the results of a study comparing the Young’s modulus, residual stress, and burst strength of polycrystalline SiC (polyc SiC) films grown on Si-wafer (610°C) and annealed (1200°C) polysilicon substrates. XRD and TEM are used to characterize the microstructure of the polyc SiC films. Polyc SiC films grown on as-deposited polysilicon are highly textured (110) films, while polyc SiC films grown on annealed polysilicon have a mixed texture comprised of (111) and (110) grains. Young’s modulus and residual stress are determined using an interferometric load-deflection measurement apparatus on suspended polyc SiC diaphragms, which are fabricated by bulk micromachining. The load-deflection data are analyzed using a least squares curve-fitting technique to extract Young’s modulus and residual stress. The value of Young’s modulus of polyc SiC depends on grain microstructure, averaging ~350 GPa for highly textured (110) films with columnar grains to ~440 GPa for equixed films with a mixture of (111) and (110) grain orientations. The residual stress of polyc SiC is independent of grain microstructure and averages ~440 MPa. Burst strength is determined using a combination of finite element analysis and burst pressure measurements of the suspended diaphragms. The burst strength values of polyc SiC diaphragms range from ~1290 GPa for films with a relatively high grain boundary density to ~1720 GPa for films with a relatively low grain boundary density.