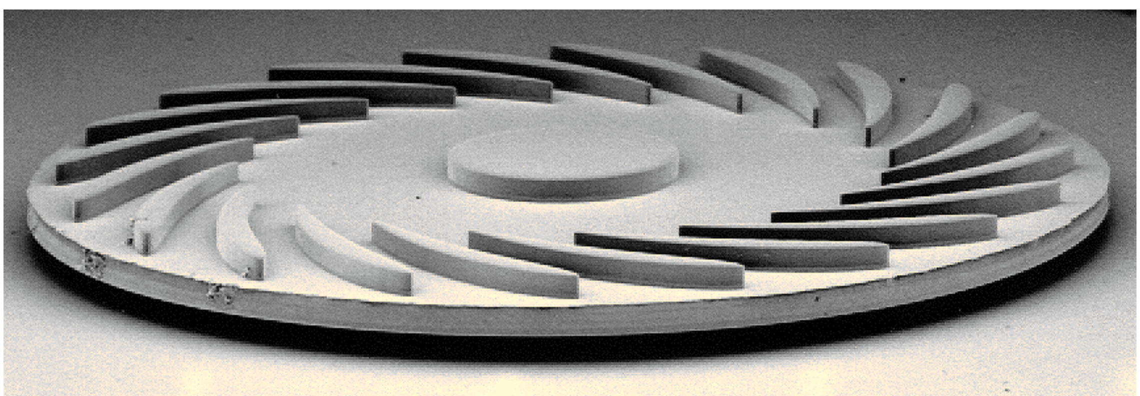
Microelectromechanical Devices



Free standing SiC microengine rotor created by CVD into an Si mold. The rotor diameter is 4 mm.
Courtesy of: K-S. Chen, D. Choi, T. Harrison, K. Lohner, B. Miller and W. Ye (S. M. Spearing)

Microelectromechanical Devices

- *Computer Microvision for MEMS*
- *Server Architecture for MEMS Characterization*
- *Image Sampling Rate Controller: Generating Strobe Pulses in MEMS Station*
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- ***Combustor and Static Structure of a Silicon Micro Gas Turbine Engine***
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Computer Microvision for MEMS

Personnel

E. Pedersen, J. Cottrell and M. B. McIlrath (D. E. Troxel)

Sponsorship

DARPA

MEMS have the potential to revolutionize the design and production of sensors and actuators. However, the ultimate introduction of MEMS into major military and commercial systems depends critically on the speed with which MEMS can be designed and delivered into the field. The paucity of test equipment now available is an obstacle to the dissemination of MEMS for increasing the nation's defense and commercial competitiveness.

We call computer microvision the combination of light microscopy, video imaging, and machine vision. We are developing a series of MEMS stations to collect image data on various MEMS devices. The series of measurement stations will have a modular structure to enable the deployment of cost-effective measurement stations for the task at hand. A relatively more expensive MEMS station will have expanded specifications. Our ultimate goal is to develop computer microvision as a useful tool for the design and manufacture of MEMS - a tool that will enable the measurement of dynamical properties of the materials used to fabricate the MEMS device, as well as to characterize MEMS components used in larger systems.

Work has begun to construct a MEMS station consisting of a pc, camera, probe station (including a microscope), stimulus generator, and strobe pulse generator. This system will provide pictures in order to analyze a candidate MEMS device. Considerable work has been done on the development of a strobe pulse generator to trigger an LED which illuminates the image to be captured. A novel technique for the generation of these pulses via a software algorithm has been proposed and will be evaluated and compared to the traditional approach using a phase locked loop.

Server Architecture for MEMS Characterization

Personnel

J. Cottrell, D. E. Troxel, and M. B. McIlrath

Sponsorship

DARPA

Designers of MEMS need good tools to test the devices they fabricate. They need to be able to characterize a device's mechanical as well as electrical properties. Unfortunately, current tools provide no automated methods of analyzing the motion of a MEMS device. This research defines and implements the server half of a remote MEMS Characterization System. It spells out the details of the system's network protocol for communicating between client and server. Finally, it describes how to deploy the server with other system components in a research environment.

Image Sampling Rate Controller: Generating Strobe Pulses in MEMS Station

Personnel

R. Rodriguez (D. E. Troxel)

Sponsorship

DARPA

In an effort to support the analysis and development of microelectromechanical systems, the Research Laboratory of Electronics at the Massachusetts Institute of Technology is building a workstation dedicated to testing and troubleshooting MEMS, the MEMS station. When the camera controlled by the MEMS station takes pictures of MEMS under stimulus, specialized hardware in the workstation generates a sequence of pulses that determine the camera's sampling rate. Phase-Locked Loop frequency multipliers provide a solution for the generation of strobe pulses in the MEMS station. The PLL communicates with the workstation using the computer's serial port. The PLL solution allows users to control the frequency multiplication factor, as well as the trigger point of the first pulse with respect to an excitation signal. This PLL solution supports sampling rate frequencies from 1 Hz to 14.1 MHz.

Microcantilever Beam Structures

Personnel

Y.K. Min and H.L. Tuller

Sponsorship

Daewoo Electronics Fellowship

Silicon microcantilever beams, coated with piezoelectric films and a variety of other active materials will be examined for their response to thermal, chemical and mechanical stimuli.

Microelectromechanical (MEMS) Thin Film Stress Sensors

Personnel

S. Seel, M.J. Kobrinsky, R. Bernstein, Y.H. Lau, and E. Deutsch (S. Senturia and C.V. Thompson)

Sponsorship

NSF, SRC

We have designed and fabricated two types of MEMS devices for the measurement of stresses in films during deposition and in-situ annealing. One class of devices uses micromachined single crystal microcantilevers with three resistors and one piezoresistor in a Wheatstone bridge fabricated in the cantilever. Piezoresistance measurements will be used to determine cantilever stresses resulting from stresses in films deposited on the cantilevers. The second type of device is based on the use of polysilicon fixed-fixed beams or cantilever beams in capacitor configurations in which the beams can be electrostatically "pulled-in" to the substrate. It has been shown that the pull-in voltage of microbeam structures is a strong function of the dimensions of the device and of the modulus and stress state of the beams. We have extended analyses of the pull-in process for fixed-fixed and cantilever beams to account for the effects of films deposited on the beams. We have demonstrated in experiments that fixed-fixed beam structures can be used to measure stresses of less than 3MPa in 1000nm-thick films and less than 30MPa in 100nm-thick films. Cantilever piezoresistor and pull-in structures are expected to have substantially higher sensitivities.

Microelectromechanical Test Structures (M-Test)

Personnel

E. Deutsch, A. Volpicelli, R. Sood (S. D. Senturia), in collaboration with the research group of C. Thompson

Sponsorship

SRC and DARPA

The goal of this project is the development of a micromechanical "drop-in" pattern, analogous to the set of test structures used in microelectronics for measuring transistor parameters, which can be used to monitor MEMS process uniformity and repeatability, and to determine the mechanical properties of micromechanical materials. The method used is called "M-Test", in which the dependence of electrostatic pull-in voltage on device geometry is used as the primary measurement.

Previously developed quantitative models for pull-in of highly ideal structures, of the kind that can be fabricated with wafer bonding methods, were reported by Osterberg. These models have been demonstrated as effective methods of material property measurement in devices that satisfy their geometric assumptions. These methods have now been extended to structures with built up, somewhat compliant supports, and to materials, such as polysilicon, that exhibit residual strain and strain gradients through their thickness. And we have significantly improved the accuracy of the metrology, so that the precision of extraction of Young's modulus is about 3%. However, the mean value of polysilicon modulus we obtain differs from that obtained by Sharpe using tensilometry by about 9%. Therefore, we have been examining the M-Test procedure for small residual modeling errors. In particular, with Mauro Kobrinsky of Prof. Carl Thompson's group, we have shown that compliant beam supports, in combination with residual stress (and also stress gradients), produces small amounts of bending of the beams, determined from WYKO profilometer measurements to be of order 100 nm. This small out-of-plane distortion may shift the pull-in voltages slightly, which would create a small systematic error in the extraction of stress and modulus. Quantitative analysis of this effect is under way. In the mean time, M-Test is extremely useful as a process control monitor, since it depends both on geometry and material properties. Variations in either will shift the observed pull-in voltages.

Because M-Test measurements require collection of large amounts of data, effort has been directed toward automa-

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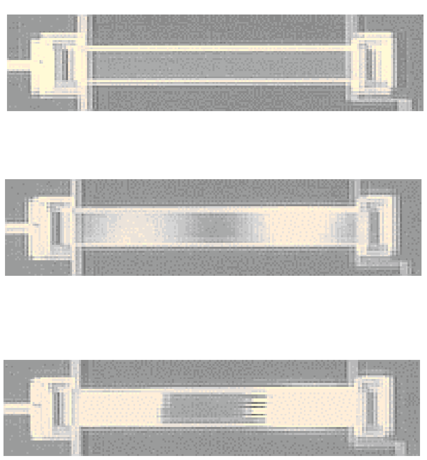
tion of the procedure. A chip design with a contact pad array suitable for use with a probe card was created, and a set of programmable voltage sources, multiplexers, and precision voltmeters was assembled to permit complete M-Test actuation and data collection under computer control. The critical step is the detection of the pull-in event itself. We have developed a computer-vision algorithm that detects the pull-in event as a sharp change in contrast when the beam under test is viewed through Nomarski optics (see Figure 1). Using a CCD camera and analysis of the contrast of selected regions of interest in each frame, pull-in can be automatically detected with a precision of 10 mV. Further, a complete set of beams of varying length can be tested automatically, with the resulting pull-in vs. length data analyzed to extract residual stress and elastic modulus. The effect of these improvements is that the M-Test method is now completely compatible with standard automatic test equipment in an industrial environment. These results will be presented at the International Conference on Solid-State Sensors and Actuators (Transducers '99) in Sendai, Japan, in June 1999.



CAD for Microelectromechanical Systems (MEMCAD)

Personnel

L. Gabbay and J. Mehner (S. D. Senturia), in collaboration with the research group of J. K. White and with Microcosm Technologies

Sponsorship

DARPA

The goal of this project has been to create a CAD system which is directed toward mechanical and electromechanical aspects of microsystem design. The MIT MEMCAD system has been licensed to Microcosm Technologies, Inc. for commercial distribution. Continuing work at MIT has focused on new classes of problems that will enhance the breadth of device applications for MEMCAD.

Perhaps the most critical need in such systems is the ability to construct low-order dynamic macro-models of device behavior that can be used in system-level simulators (such as SPICE), while maintaining consistency with the true behavior as represented by meshed simulation. The TCAD portion of the MEMCAD system generates the device shape based on masks and process information, and the device simulators evaluate responses to applied loads in a highly meshed, numerically intensive environment. At the system level, however, where it is desirable to connect the MEMS device into circuits, and to understand the effects of feedback, accurate and energetically correct low-order dynamical behavior models are needed, either in the form of equivalent lumped circuit models, or as a small number of coupled Ordinary Differential Equations (ODE's).

We have previously reported on use of basis-function methods for the construction of dynamic macro-models, including an algorithmic procedure for automatically creating representations of electrostatic actuation and elastic behavior directly in basis-function space, leading to a small number of coupled ODE's that completely describe the device dynamics (but without damping; a similar approach has been developed for systems with dissipation, but the resulting ODE's are more complex, and require transformation to configuration space at each time step). The ODE's are written in a form which permits direct insertion into circuit simulators as a single function block, so that effects of an external circuit and feedback loop can be simulated. This method is now

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being extended to magnetic MEMS devices (see "Dynamical Macro-Models for Magnetic MEMS Devices").

For the electrostatic case, the approach turns out to be extremely successful for MEMS devices that execute small motions, but it fails to describe correctly the phenomenon of "stress stiffening," when a clamped device executes motions greater than a typical thickness dimension. We have now developed a procedure for analyzing stress-stiffened structures using basis functions. The method will apply to any MEMS structure for which the motion is described by a single dominant deformation mode. The method produces macro-models in terms of a few coupled ODE's, but the procedure for calculating the stiffness for the various dynamical

Dynamical Macro-Models for Magnetic MEMS Devices

Personnel

M. Varghese and M. Hill (S. D. Senturia) in collaboration with the research groups of J. K. White (MIT), J. Gilbert (Microcosm Technologies), and M. Allen (Georgia Tech)

Sponsorship

DARPA and Sandia Labs

The MIT MEMCAD System has emphasized quasi-static 3-D numerical simulations of meshed structures as the basis for device modeling. However, designers typically prefer to work with dynamical analytical models with only a few degrees of freedom; we refer to these as "macro-models."

There has already been extensive work on automatic generation of macro-models for electrostatically actuated deformable elastic structures (see "CAD for Microelectromechanical Systems (MEMCAD)"). We are now extending these concepts to devices that incorporate magnetic interactions, either for sensing or actuation.

In our DARPA-sponsored program, we are examining a set of magnetically actuated devices based on the Lorentz-force and also devices based on linear permeable material. The goal is to develop macro-modeling methods, analogous to what has already been achieved for electrostatically actuated devices, for this class of magnetic devices. This program involves close collaboration with Prof. J. White at MIT and the Microcosm group for the development of boundary-element simulation tools for Lorentz-force and linear-permeable cases, and with Prof. M. Allen of Georgia Tech whose group will be fabricating and characterizing a new class of test structures designed by our group.

Results to date include confirmation that the FAST-HENRY tool developed by Prof. White's group yields quantitatively correct results for a variety of micromachined air-core coil structures, and the design of a new set of Lorentz-force actuators to be fabricated at Georgia Tech. In addition, the method of Gabbay used for automatic macromodel generation for electrostatically actuated devices has been demonstrated for the case of Lorentz-force actuators, including such effects as magnetic pull-in. This latter result is being presented at MSM99 in Puerto Rico in April 1999.

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In a related project sponsored by Sandia Labs, we are using the MEMCAD system to examine the resonant behavior of a set of Lorentz-force-actuated flexural plate wave resonators. The devices were fabricated and measured at Sandia; work is proceeding on correlating experimental observations of resonant modes with the results of simulation.

Enhancing MEMS Design Using Statistical Process Information

Personnel

W. P. Moyne (D. S. Boning and D. E. Troxel)

Sponsorship

DARPA

Microelectromechanical Systems (MEMS) design is often done using circuit design rules for layout and complex synthesis or mechanical simulation for actual device structure. The problem with this approach is that devices that work well in simulation often have high sensitivity to process variation and therefor can have properties that differ substantially from projected values. These effects lead to both poor performance and lower yields.

Figure 2 shows a picture as well as a diagram of a comb-drive resonator. This device is ideal for process sensitivity analysis because its resonant frequency is a key system parameter that can be easily computed in simulation and is directly affected by the process and underlying geometries.

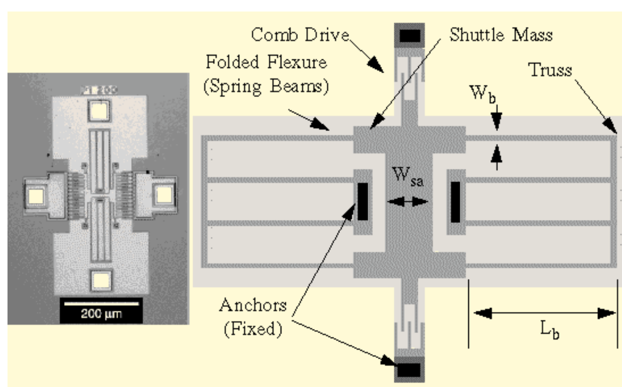

Fig. 2: Comb-Drive Resonator

As an example of the importance of process variation to device performance, Figure 3 compares a 50Khz resonator based on a 2 mm folded beam flexure to a 50Khz resonator using a 4 mm beam. The graph shows that for a 1 σ manufacturing variation in beam width (taken from actual MEMS fabrication data), the 4 mm system experienced a 4.2% frequency variation compared to 10%

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variation for the 2 mm system. This reduction in system variation (for frequency) would lead to higher yield and tighter system specifications.

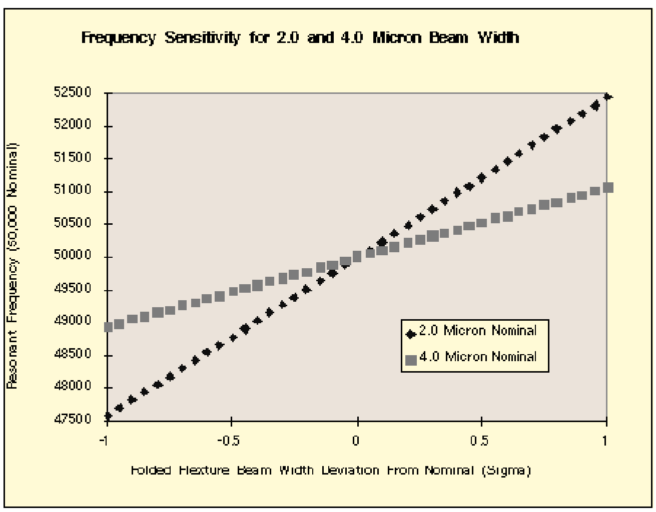

Fig. 3: 2.0mm vs. 4.0mm Folded Beam Resonator

The proposed research will address the effects of process variation in two ways. First, an elegant storage and retrieval mechanism will be implemented that enables remote repositories of statistical process information to be maintained. This solution eliminates data synchronization errors that can occur if designers copy process statistics and are unaware of later changes or additions to this information. Second, a tool will be developed that evaluates MEMS designs for robustness in the face of process variation. Process information will also be used to augment current device synthesis tools to increase the yield and manufacturability of synthesized devices.

Quasi-Static Modeling of Electrostatic Actuators

Personnel

E. Hung (S. D. Senturia)

Sponsorship

DARPA

Electrostatic actuation is very attractive for microelectromechanical systems because of good scaling properties to small dimensions, high energy densities and relative ease of fabrication. A particular class of electrostatic actuators, in which parallel-plate capacitors are used, can suffer from an instability known as pull-in. The pull-in effect can severely limit the usable range of positions that can be controlled in a continuous fashion. For a simple parallel plate capacitor with gap g having a single moveable plate suspended by a linear spring, the pull-in instability limits the usable travel to g/3. This creates severe difficulties for actuator design.

We have already reported on several ways of overcoming the pull-in limitation, using leveraged bending, and using zipper actuators. In a new result, we have observed that when a device operates in the stress-stiffened regime, the controllable travel before pull-in can be increased to slightly more than 50% of the gap. This offers some potential flexibility in the design of large-travel electrostatic actuators.

The Polychromator: A MEMS Correlation Spectrometer

Personnel

E. Hung, E. Deutsch and A. Volpicelli (S. D. Senturia), in collaboration with Honeywell Technology Center and Sandia National Laboratory

Sponsorship

DARPA

There are a number of promising applications for MEMS devices in the field of optics. This project explores a particular application in infrared spectroscopy. The basic concept is to use a linear array of mirrors, each one of which can be vertically positioned throughout a gap of several microns. By adjusting the relative positions of the mirrors, it is possible to create a special kind of diffraction grating such that incident light is diffracted into a selected viewing angle at multiple wavelengths (hence the name, "Polychromator"). In particular, it is possible to create artificially the absorption or emission spectrum of a target molecule. Then, by modulating the lines in the target spectrum, one can build a new kind of correlation spectrometer — one which uses artificially created spectral features to correlate with the presence or absence of specific absorption lines in the incoming light. The Polychromator has many advantages over conventional correlation spectroscopy: (1) the Polychromator replaces the reference gas cell with a synthetic spectral device that can be programmed for many different species; (2) it is easy to modulate compared to gas cells; (3) by using the emission spectrum instead of the gas-cell absorption for the correlation, the overall intensity is lowered, reducing detector shot noise; and (4) interferences between species can be omitted from the synthetic target spectrum by design.

The Polychromator is being developed by a joint MIT-Honeywell-Sandia Labs team. MIT is responsible for device design, selected fabrication steps, electromechanical testing, and device control software. Since the device is fabricated with surface micromachining, which limits thicknesses of gaps to several microns, it is important to be able to achieve controllable travel across the full gap without encountering pull-in. A design that achieves this end, based on the principle of "leveraged bending" has been designed and tested. And while actuation of 1cm long, 10 micron wide mirror elements has been demonstrated, process robustness has led us to adopt a modified process that involves Chemo-Mechanical Polishing (CMP) for planarization. We have recently completed a CMP planarization study, and are now incorporating MTL's CMP into the complete polychromator process.

Measurement of Shear Stress and Temperature in complex flows using Platinum-based thermal sensors

Personnel

R. Bayt (Kenneth Breuer)

Sponsorship

DARPA & AFOSR

Fluid shear stress information can be used to determine the drag force on aerodynamic models. Flush mounted hot-film sensors provide an non-intrusive means of measuring the fluid shear. By resistively heaing a thin film on the surface beneath a flow, the shear stress can be inferred from the power dissipated due to convective cooling. Traditional "hot film" sensors such as this suffer from large parasitic heat losses due to conduction to the supporting substrate and along the electrical leads. In addition, traditional thermal resistors have relatively large thermal mass and thus have limit bandwidth.

By microfabricating the sensor, improvements in performance are threefold. The resistors can be fabricated from thin metal films, and have a thermal mass several orders of magnitude less than conventionally-fabricated devices. This allows the sensor to respond to higher frequency fluctuations in the flow. This also allows the conduction losses through the leads to minimized due to their low cross-section. Secondly, the resistors are patterned on a thin (1500 Angstrom) silicon nitride membrane that spans an evacuated cavity. The vacuum cavity eliminates conduction and convection losses to the underlying substrate, while the thin membrane greatly limits the conduction losses along the membrane surface. Finally, the sensors can be batch-fabricated in arrays to enable simultaneous measurements for control and statistical modeling.

The identical process sequence can be used to make a temperature sensor. Two additional leads can be used to sense the voltage drop across the resistor. As the resistance changes with ambient temperature, this will be reflected in a variation of the voltage

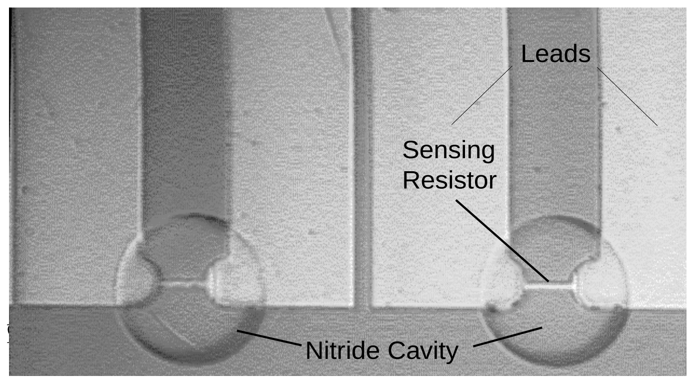

Fig. 4: Optical micrograph showing a pair of shear sensors side by side. The platinum sensor element is visible over the 210micron diameter vacuum-backed cavity.

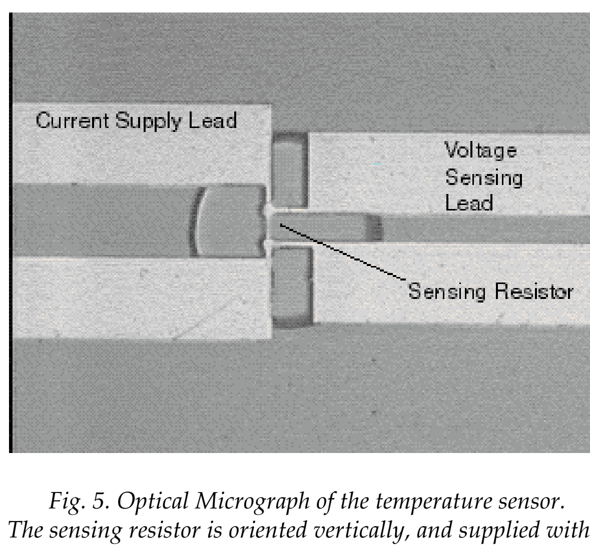

Fig. 5. Optical Micrograph of the temperature sensor. The sensing resistor is oriented vertically, and supplied with a fixed current by the leads to the left. The right leads are at a floating potential and used to measure voltage drop which will change as the temperature of the sensor element changes.

Development of Micro Hydraulic Transducer Systems

Personnel

J. Carretero, K.-S. Chen, F. Ganji, H. Li, R. Mlcak, D. Roberts, and Y.-H. Su
(N. W. Hagood, K. S. Breuer, M. A. Schmidt, and M. Spearing)

Sponsorship

DARPA

Micro Hydraulic Transducer (MHT) systems are being developed for the purpose of achieving actuators and power harvesting systems with unprecedented power densities. Actuators apply forces to structures to alter their current states, while power harvesters extract energy from the ambient environment. Typical applications of structural actuation include vibration suppression of helicopter rotor blades, reduction of acoustic transmission through panels, and control of aerodynamic surfaces on airfoils, ships, and submarine hulls. Potential applications of power harvesting devices include systems mounted in the heel of a boot to harness energy created with human movement or power extraction from thermally induced pressure changes in gas chambers on spacecraft and satellites.

These MHT systems merge three enabling technologies and ideas: solid-state transducer materials, MEMS microfabrication capabilities, and hydraulic power rectification. Solid-state transducer materials, specifically single crystal ferroelectrics, possess inherently high energy densities in converting electrical energy to mechanical energy and vice-versa. MEMS microfabrication processes and techniques allow for the realization of complex miniaturized devices and systems. Hydraulic power rectification involves the use of active valves and a working fluid to either (1) convert high frequency, small displacement solid-state transducer material vibration into lower frequency, higher stroke actuation or (2) convert low frequency large amplitude pressure fluctuations into high frequency transducer material excitation. Miniaturization of these systems results in increased component natural frequencies and therefore enables greater power conversion rates.

Current work is focused on the development of a soldier system heel-strike energy harvesting device capable of generating 1 Watt of continuous power for nominal soldier activity. The device, which will fit within the heel of a soldier's boot, is comprised of Si and Pyrex layers, bonded together to form chambers, cavities, and pathways in the system. The device is entirely self-contained (excluding electrical leads carrying power from the device) and consists of a high pressure fluid reservoir, two actively controlled fluid valves, an energy harvesting chamber, and a low pressure fluid reservoir. The energy harvesting chamber incorporates a solid-state energy transducing element between a Si base plate and Si piston diaphragm. Energy is available to the system in the form of pressure created in the high pressure reservoir as a result of a low frequency soldier step. The valves are operated out of phase with one another at high frequency (~10kHz) to allow cyclic pressure "pinging" of the energy transducing element and therefore generation of electrical energy. Cyclic behavior in this manner results in net fluid flow through the device from the high pressure reservoir to low pressure reservoir. Between steps, the accumulated fluid in the low pressure reservoir is exhausted back to the high pressure reservoir.

Micromachined Supersonic Nozzles for Space Propulsion

Personnel
R. Bayt (K. Breuer)

Sponsorship
NASA/JPL & AFOSR

The current trend in the spacecraft industry is to reduce a satellite's life-cycle cost by reducing its complexity. This is done by reducing the number of instruments, and reducing the mass of supporting subsystems. This, combined with the increasing miniaturization of components, has spawned the microsatellite revolution. The goal is to develop functional spacecraft under 10 kg utilizing 10 Watts of power. Our work furthers these goals by demonstrating a MEMS-based micropropulsion systems for use in attitude control of these spacecraft.

The early focus was to demonstrate a micronozzle for accelerating gas to supersonic velocities. The contoured converging-diverging micronozzles were fabricated through deep reactive ion etching with throats of 18 and 37 microns. Considerable effort was focused on achieving an anisotropic etch of a feature of variable geometry of these dimensions. The nozzles were tested at various flow rates and the thrust efficiency was found to agree within experimental error to a 2-D simulation of viscous flow in the contoured channel at high flow rates, and deviate considerably at low flow rates. This is due to the increased viscous effects at low flow rates, which translates into an increased influence of boundary layers on the endwalls, which are not modeled in a 2-D calculation.

Second generation nozzles are to be run with the gas resistively heated to 900°C prior to injection into the nozzles. The increased chamber energy will increase momentum transfer for the same mass flow rate. This results in higher fuel efficiency, by trading one spacecraft consumable (propellant) for another (power). The spacecraft power is replenishable through the power generated by the solar arrays, but the propellant is the life-limiting element of the spacecraft.

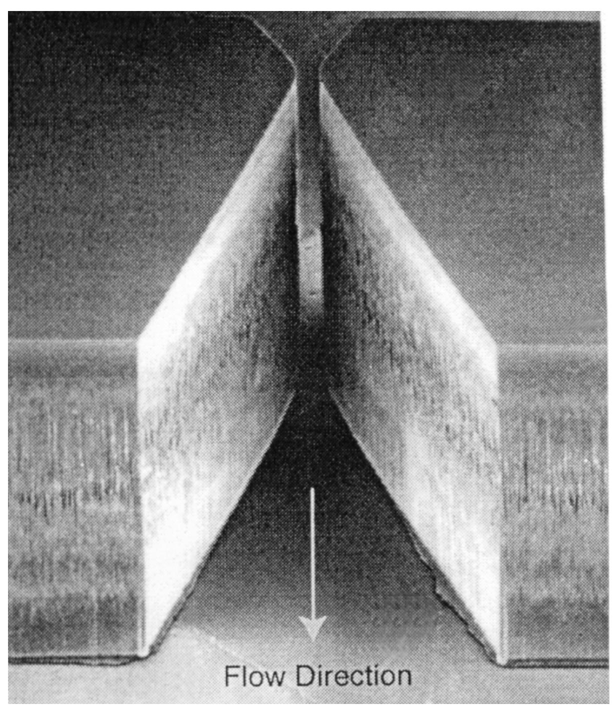

Fig. 6: DRIE etched nozzle with a 19 um throat width and 308 mm deep. Upper and lower surface are anodically bonded to Pyrex to enclose the flow channel and allow gas to be discharged from the edge of the die.

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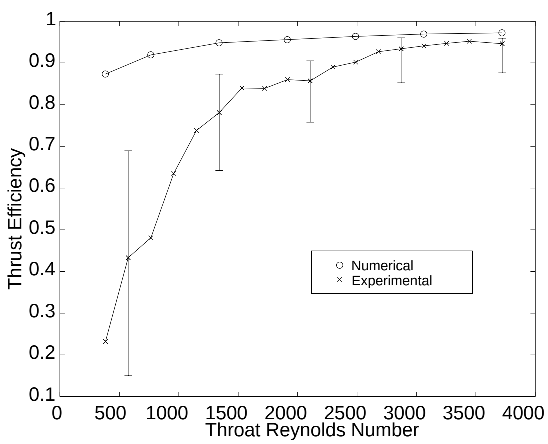

Fig. 7: Performance of the system is established with the thrust efficiency, or the ratio of measured or simulated thrust to the ideal. The Reynolds number is a function of the mass flow rate, and scales the influence of viscous forces. When the viscous losses are high, the influence of the unmodeled interaction of the flow with the endwall causes the test results to deviated from the simulation.

Sputter Deposition of Piezoelectric AlN Thin Films for Chemical and Biological MEMS Sensors

Personnel

W. Mao (R. Reif)

Sponsorship

Draper Laboratory

Low-temperature deposited aluminum nitride thin-films can be used in many novel Si integrated devices including biological and chemical MEMS sensors. Aluminum nitride is advantageous for MEMS use, because it can be deposited at low temperatures, is easily patterned using conventional photolithographic techniques, and is CMOS compatible.

0.5µm AlN films are deposited on Si membranes for use in flexural plate wave gravimetric sensors. Interdigitated transducers act on the piezoelectric AlN layer to launch and detect flexural plate waves across the membrane. The Si membranes are coated with binding-site specific polymers; exposure to target chemicals results in an increase in membrane mass. This mass change is detected as a change in the membrane resonant frequency.

Previous work at MTL in support of the Draper chemical and biological sensor project has resulted in a working protocol for the deposition of 0.5 µm low stress piezoelectric aluminum nitride (AlN) films and a greater understanding of the relationship between film properties and deposition parameters. As device design and specifications change, it is crucial to maintain production of high quality films which are an integral component of the Draper chemical and biological sensors. Further research toward understanding the mechanisms controlling film growth and properties is also necessary in order to have the capacity to produce films of similar quality in other sputtering systems. 0.25 µm films will also be investigated since device sensitivity is dictated by membrane mass and hence the membrane thickness making reduction in the AlN film thickness is desirable for increased device sensitivity.

Integrated Sensors

Personnel

C-F. Yung and K. Ishihara (M.A. Schmidt)

Sponsorship

SRC, DARPA

This project explores the development of technologies that permit the monolithic integration of circuitry with micromechanical devices. The core technologies being used are aligned wafer bonding and Deep Reactive Ion Etching (DRIE). The overarching goal of this work is to develop a technology set that permits seamless integration with foundry processes for the circuit integration. This goal is driven by the practical realities that wafer volumes for MEMS devices can be low, and thus not sufficient to support a full IC facility. Compatibility with foundry processes would permit a more effective low-cost product for markets which benefit from the monolithic integration of circuits plus sensors.

We have investigated two device drivers; a two-axis accelerometer, and a z-axis gyroscope. The two-axis accelerometer is designed with typical specifications for an air-bag detection system in vehicles. The z-axis gyroscope (designed through a collaboration with the Berkeley Sensors and Actuators Center at the University of California at Berkeley) is intended for higher precision applications, wherein the thick structural layers (greater than 100 microns) afford much lower noise floors than comparable devices built in polysilicon. Both the gyro and the accelerometer have been built (without electronics) to verify the mechanics and the post-IC processes. The process has yielded functional devices in both cases. In the coming year we will begin the integration activities using a foundry CMOS process.

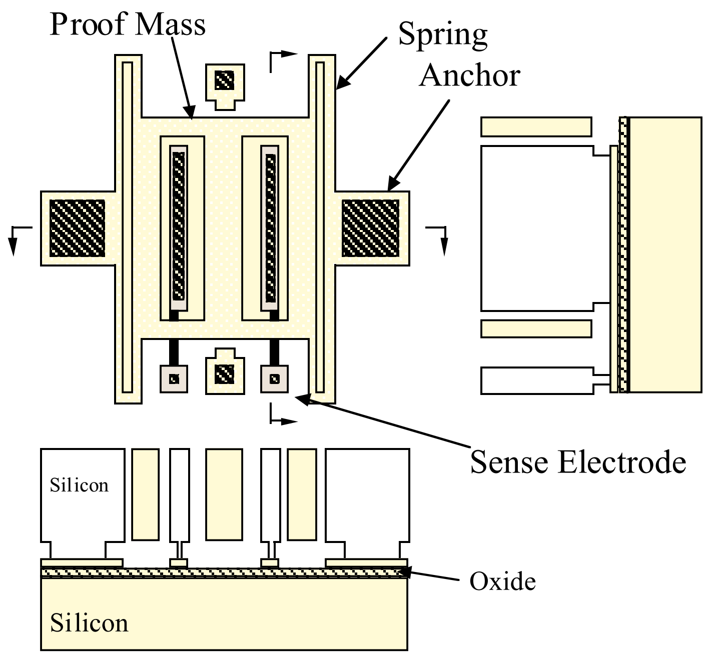

Fig. 8: A schematic illustration of an accelerometer

Wafer-Level Packaging

Personnel
C. Tsau (M.A. Schmidt and S.M. Spearing)

Sponsorship
DARPA

Packaging costs often dominate the total cost of a system based on MEMS devices. Thus, tremendous cost leverage is possible by addressing fundamental changes in the methods of packaging of MEMS devices. We are pursuing wafer-level packaging approaches that take advantage of the economy of batch fabrication. In other words, when the packaging is accomplished at the wafer level, the cost of that packaging operation is distributed over the 1000+ devices on the wafer, thus significantly lowering cost.

We are exploring the fundamental properties of a wafer-level thermocompression bond. This bond is performed by pressing two silicon wafers with thin patterned gold films together in such a way that the gold films deform and bond. The bond is performed at 300-350C, permitting it to be performed after integrated circuits and MEMS devices have been formed on the wafer. In addition, because the bond layers are conductors, the bonding layers may also be used for local signal routing. Lastly, it is possible that the bonding can be performed in a vacuum, which can be critical to the operation of some inertial sensors.

Thus far, we have established a wafer-level bonding protocol for 4" wafers using a commercial bond tool (Electronic Visions). Additionally, we have developed a bond strength measurement technique which permits a direct measure of the de-bond energy. The future work include mapping the bond quality over a range of process conditions, bonding in vacuum, and assessing the local interconnect capability of the bond.

Microfabricated Cell Sorter

Personnel
R. Braff and J. Voldman
(M.L. Gray, M.A. Schmidt and M. Toner)

Sponsorship
NSF

Microfabrication technology has the unique capability of producing arrays of devices as well as devices that are of the dimensions of biological cells. In this project we are exploring methods for cell capture and release that leverage these capabilities and could be productively deployed in a miniature biological instrument for diagnosis. Two approaches are being investigated for cell capture and release. The first uses hydraulic forces generated by MEMS actuators for cell manipulation. The second uses DielEctroPheresis (DEP) forces. DEP forces can drive cells to electric field extremes. For example, by creating a planar quadrupole electrode array, it is possible to spatially confine cells for further investigation and sorting. We plan to develop and document the performance of these cell capture mechanisms with an eye towards a cell sorting instrument.

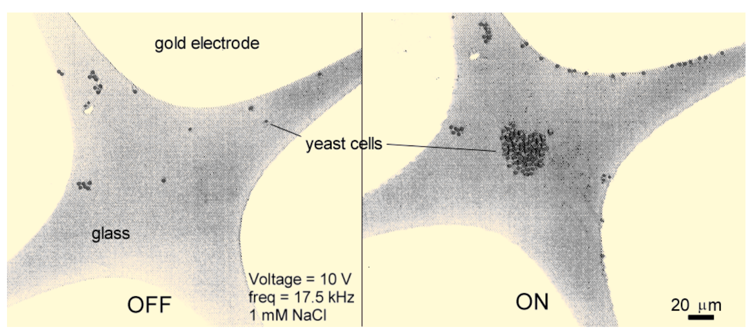

Figure 9: DEP sorting of cells. An electric field is turned on and the yeast cells are driven to the center of the electrode pattern.

The Microturbine Generator

Personnel

C. Livermore, (S. D. Senturia), in collaboration with R. Ghodssi, S. Nagle, L. Frechette, J. Lang, and S. Umans

Sponsorship

ARO, DARPA

The MIT Microengine Project has the goal of creating a fully microfabricated gas turbine engine, complete with combustor, compressor, turbine, and an electrostatic generator mounted on the shroud of the compressor. This project is concerned with the design and fabrication of the electrostatic generator, using as a starting point the work of Nagle, Frechette, Lang, and Umans (with the assistance of the Microengine fabrication team headed by Ghodssi) on induction micromotors. The first task was, in collaboration with Nagle, to develop a reliable process for fabricating the rotor conductor material. In electrostatic induction motors, both the sheet resistance and dielectric relaxation time of this material must match narrow windows for optimum performance. Appropriately doped coarse-grained polysilicon was selected after a variety of trials.

An equally critical problem is the design of the stator. Based on motor models developed by Nagle, Lang, and Umans, we have determined that heavily-doped polysilicon as a stator interconnect and electrode material is too resistive for effective generator operation. As a result, we have begun the development of a two-level-metal process for the stator, using tungsten for the metal and deposited oxide for the dielectric.

Micro Electric Machines for Micro Turbomachinery

Personnel

S. F. Nagle, L. Frechette, R. Ghodssi, C. Livermore, X. Zhang and A. Ayon (J. H. Lang, S. D. Senturia, S. D. Umans and E. P. Warren in collaboration with K. S. Breuer, F. E. Ehrich, A. H. Epstein, S. Jacobsen, M. S. Spearing, C. S. Tan, and I. A. Waitz)

Sponsorship

ARO and DARPA

This project is part of the MIT Micro Gas Turbine Engine Project. The MIT Micro Gas Turbine Engine Project has the ambitious goal of using MEMS fabrication technologies to construct compact electric power generation systems from a gas turbine generator comprising a compressor, combustor, turbine and electric generator. Other systems under development include separate motor/compressors and turbine/generators. The MIT Micro Gas Turbine Engine Project is highly interdisciplinary, involving students, staff and faculty from several academic departments and laboratories.

This project seeks to develop the motors and generators employed in the micro turbomachines mentioned above, and to develop their power and control electronics. Following the analysis of several candidates, we have selected the electric induction machine for these applications. Our electric machine is disk-shaped, and is shown in edge view in Figure 10. On one side of its air gap, polysilicon stator electrodes are supported by a thick silicon-dioxide insulator buried in a substrate. The electrodes are connected to form one or more phases, and are excited so as to impose a potential wave which travels around the stator. On the other side of the air gap is the rotor, which rotates as a disk. The rotor consists of a conducting polysilicon film supported by an silicon-dioxide insulator buried in a substrate.

During motoring operation, the power electronics excite the stator electrodes to produce a potential wave which travels around the stator with a speed exceeding that of the rotor. This wave, and the corresponding charges which reside on the stator electrodes, induce image charges on the rotor surface across the air gap. Since the speed of the traveling potential wave exceeds the mechanical speed of the rotor, convection alone can not synchronize the rotor charges with the traveling wave, as must happen in steady state. Thus, the rotor charges must conduct through the rotor film to maintain synchronism. The conduction process must in turn be driven by a tangential electric field, and so the rotor charges lag behind the potential wave to produce that field. Finally, the tangential electric field acts on the rotor charges to impart a tangential surface stress on the rotor, which in turn results in a motoring torque. During generating operation, the rotor speed exceeds that of the traveling potential wave, and the torque is reversed.

To date, we have derived detailed dynamic models of

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the electric induction machine, and have used those models to design an optimized 6-phase machine having a 4-mm diameter. As a motor, we expect this machine to produce a 3-W mechanical output at 2.4 Mrpm when its phases are excited with 300-V 3-MHz sinusoids. To support this design effort, we have characterized the conductivity of the polysilicon rotor film and the electrical breakdown of the air gaps between the stator electrodes, and we have developed a process through which thick films of silicon dioxide may be buried in wells etched into a silicon substrate. Finally, we have designed, fabricated and demonstrated control electronics and resonant power electronics to support motoring operation.

Our work now focuses on the fabrication and testing of several experimental motors including a tethered motor and a motor/compressor. A drawing of the tethered motor is shown in Figure 11. In this motor, the rotor is stationary, and is supported by mechanical tethers, or springs, which are approximately ten microns thick and etched through the entire rotor substrate. The bending of the tethers will be used to accurately measure torque.

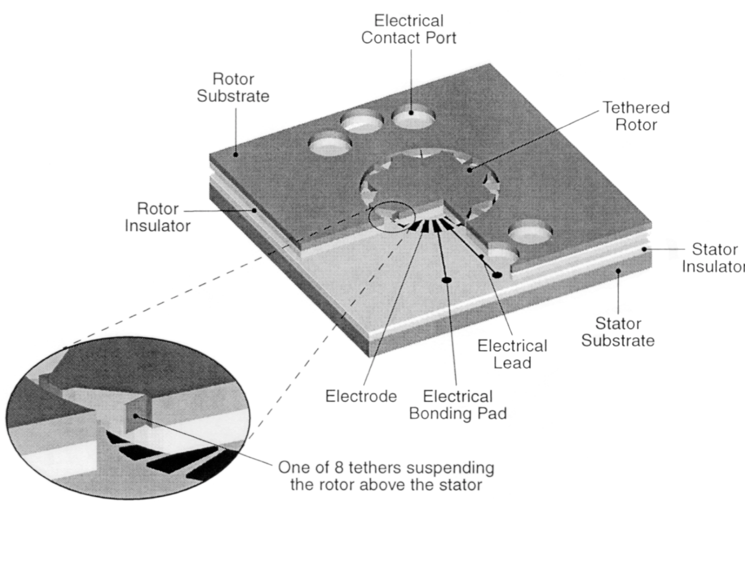

Fig. 11: Perspective view of the tethered electric induction motor.

Combustor and Static Structure of a Silicon Micro Gas Turbine Engine

Personnel

A. Mehra, A. Ayon, C. Cadou, J. Lee, S. Lukachko, X. Zhang (I. Waitz)

Sponsorship

Not Listed

Recent advances in silicon microfabrication technology have led to the realization of miniature heat engines for portable power generation and micro air vehicle propulsion [11] & [12]. As part of a program to develop a button-sized micro gas turbine engine capable of providing 10-50 Watts of electrical power in a 1cm^3 package, we have completed the design, fabrication and initial testing of the first engine static structure micromachined from silicon.

Comprising all the non-rotating functional components of a Brayton-cycle based gas turbine engine, the device measures 2.1 cm × 2.1 cm × 0.38 cm, and is aligned-fusion bonded from 6 silicon wafers. As shown in Figure 12, this static structure is the first demonstration of the entire hot flow path of a 6-wafer multi-level microengine, and is fully-compatible with the thermal, structural and fabrication constraints of the final engine configuration. Fabricated largely through the use of Deep Reactive Ion Etching (DRIE), the structure required anisotropic dry etching through a total thickness of 3,800 μm. Complete with a set of fuel plenums, fuel injector holes, pressure ports and compressor and turbine static blades, the design of the static structure required a multi-disciplinary approach that accounted for all the chemical, structural, fluidic, and materials fabrication aspects of the engine. Detailed SEMs of the 6 wafers prior to bonding are shown in Figure 13 to illustrate the fluid flow path.

For the propulsion and power generation applications of interest, the principal figure of merit for the propulsion system is the power density. The device has been shown to sustain hydrogen-air combustion in a chamber measuring 0.195 cm^3 in volume with exit gas temperatures as high as 1725K. The resulting power density of the combustion system is at least an order of magnitude higher than any other previously reported power-MEMS device. Combined with high temperature testing that showed no visible degradation after 6 hours of operation, these results establish the viability operating a silicon static structure for an emerging class of high power density micro heat engine applications. Efforts are currently underway to continue experimental testing to understand the combustion stability boundaries for hydrogen and hydrocarbon fuels, and to integrate the static structure with the rotating components of the engine. Efforts are also underway to develop on-chip igniters

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and temperature sensors using polysilicon resistive elements, and to design and fabricate catalytic hydrocarbon combustors that employ microfabricated silicon carbide structures and catalytic coatings.

(The first public report of this work will be presented at the Transducers'99 Solid-State Sensors and Actuators Conference.)

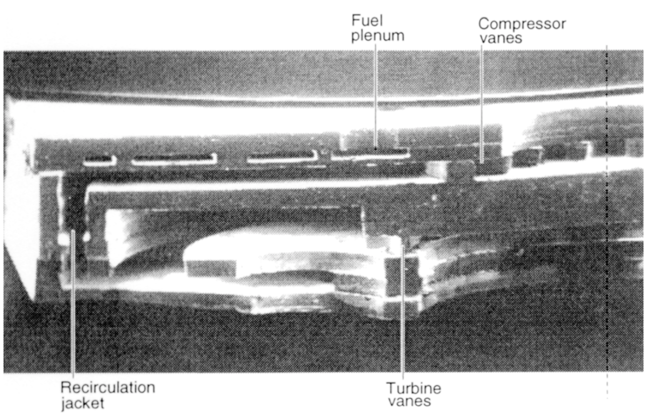

Fig. 12: Schematic and SEM cross-section of half of the axisymmetric 6-wafer static structure.

Power MEMS Materials and Structures

Personnel

K-S. Chen, D. Choi, T. Harrison, K. Lohner, B. Miller and W. Ye (S. M. Spearing)

Sponsorship

DARPA and ARO

Material characterization, thermo-structural analysis, refractory ceramic microfabrication process development and packaging technology development are proceeding in support of several power MEMS programs including; the microengine, motor-compressor and microservohydraulic transducer projects. The potentially very high power density of these devices is predicated on the mechanical elements withstanding very high stress levels. In addition devices such as the microengine are designed to operate at high temperatures, and its performance is determined by the strength, creep and oxidation of its constituent materials. Since silicon and refractory ceramics are very brittle, and therefore variable, materials it is essential to obtain strength data from specimens which have been fabricated by the same process and at similar sizes to the intended application. Mechanical tests methods have been developed for probing the room temperature strength of microfabricated materials with particular emphasis on the local strength at stress concentrations and the relationship between strength and processing route. Elevated temperature strength and creep data have been obtained for silicon in the operating temperature range of the microengine. Work has been initiated to identify the dependence of wafer bond toughness on processing conditions. The mechanical test data are being combined with structural and heat transfer finite element analyses of the microengine and microservohydraulic transducer components in order to verify the overall structural integrity of the designs using probabilistic methods.

Significant progress has been made in developing molding techniques with which to create SiC structures by chemical vapor deposition into deep reactive ion etched molds. An example of this technique is the free standing SiC microengine rotor shown in the figure below. In addition high temperature packaging technologies are being developed with particular emphasis on fluid interconnections for these devices.

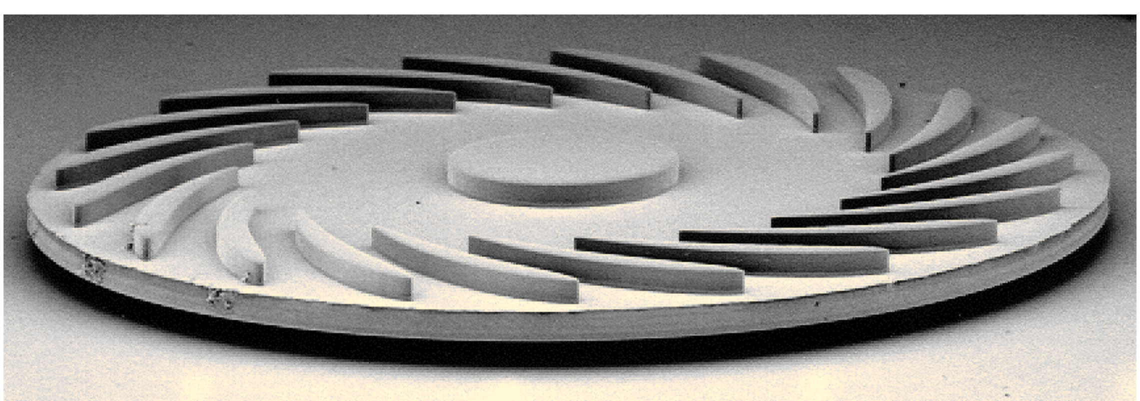

Fig. 14: Free standing SiC microengine rotor created by CVD into an Si mold. The rotor diameter is 4 mm

Fabrication and Testing of a Air-Powered Turbine supported by Gas Bearings

Personnel

C.C. Lin, D.J. Orr, E.S. Piekos, N. Savoulides and D.Z. Chen
(K.S. Breuer, F. Ehrich, S. Jacobson, A. Ayon, R. Ghodssi, A. Epstein and M.A. Schmidt)

Sponsorship

ARO & DARPA

As part of the MIT Microengine project, we have completed the design, fabrication and initial testing of an air-powered turbine supported on gas bearings. The device cross-section is shown below in Figure 15 which illustrates the 5-wafer stack that comprises the device. The central wafer, shown in planform in Figure 15, contains the stator blades which direct high pressure air througha radial flow turbine. Externally-pressurized thrust bearings etched into wafers 2 and 4 support the rotor in the axial direction. The rotor is supported in the radial direction by a low-aspect ratio journal bearing created by a single DRIE etch 300 microns deep and 12 microns wide. Initial testing of the device confirms that the thrust bearings can "float" the rotor which has been spun at speeds in excess of 100,000 RPM. This represents a successful first step towards our goal of spinning the rotor at speeds above 1 million RPM.

Significant analysis and modeling efforts have also been conducted in support of the fabrication activities. These efforts have resulted in a suite of analytical and numerical tools for the design and analysis of microfabricated lubrication systems. Both hydrodynamic and hydrostatic lubrication systems are being analyzed as candidates for the next generation device, currently being designed. A scaled-up (26:1) test rotor, fabricated from steel, has also been used extensively to demonstrate the capability of the design to achieve the desired high speeds and to measure the rotor dynamic properties under different operating conditions.

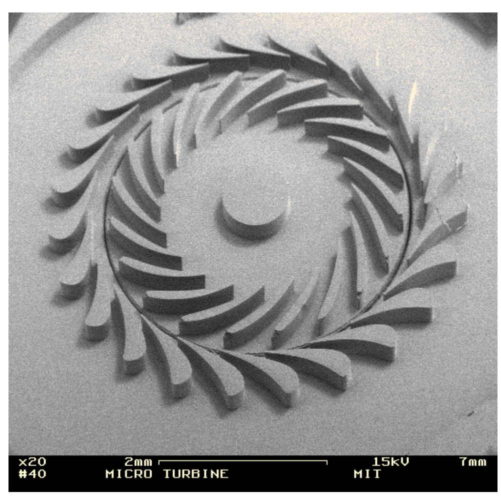

*Fig. 16: Micro-turbine rotor-stator combination.
This comprises the middle wafer of the 5-wafer stack shown above.
The rotor is 4mm in diameter.*

Microengine Fabrication Technologies

Personnel

A. Ayon, D-Z. Chen, L. Fréchette, R. Ghodssi, S. Jacobson, R. Khanna, C-C. Lin, C. Livermore, A. London, A. Mehra, S. Nagle, J. Protz, T. Takacs, X. Zhang (M.A. Schmidt), in collaboration with T. Bloomstein (Lincoln Lab)

Sponsorship

ARO, DARPA

As part of an ambitious program to produce high-speed rotating microturbomachinery for a variety of applications, we have been developing new manufacturing methods that could enable these types of devices (as well as others). The core technologies that underlie these devices are deep reactive ion etching (DRIE) and aligned wafer bonding. DRIE permits high aspect ratio extrusion of two-dimensional shapes into silicon. We have further augmented this process by developing protocols for two-sided DRIE. A three-dimensional solid object is constructed by lamination (in our case aligned wafer bonding) of multiple substrates (wafers) containing these extruded two-dimensional shapes. The devices built thus far include microbearing rigs (comprised of 16 masks, 11 DRIE steps, and 5 wafers), and a six-wafer microcombustion rig. Each of these devices is detailed in separate sections of the MTL annual report.

Development of this manufacturing methodology has required us to focus on careful optimization of all process steps, in particular since the dimensional tolerances required of the microturbine engines are quite demanding. This has necessitated extensive designed experiments on the core processes. In the case of DRIE, we have performed exhaustive mapping of the etching characteristics of our tool in the interest of obtaining etch characteristics that at times exceed even the manufacturer's specifications for the tool. Also, the photolith operations have been optimized to ensure high yield and good uniformity. Aligned wafer bonding of six wafers has been achieved through careful attention to detail, and by refinement of machine operation characteristics.

In many of the devices we wish to build, the end goal is a freely rotating silicon disk that is completely encased in silicon. This represents the challenge of how to constrain the disk during wafer processing, yet having it fully released at the end of the process. We have developed a method that relies on silicon tabs that constrain the rotor while in process. Once the wafers have been aligned and bonded, the rotor is completely contained. At this point, the rotor is released by the use of a laser-assisted etch of the silicon tabs that constrain the rotor. This process was developed in collaboration with Dr. T. Bloomstein at MIT Lincoln Laboratories.

We believe the manufacturing methods developed in this program represent a new paradigm for the manufacture of highly complicated three dimensional microsystems. Through careful attention to process technologies, it is possible to routinely produce the multi-wafer stacks that we have created thus far. This process greatly expands the range of MEMS devices that can be fabricated.

Microelectromechanical Relays

Personnel

J.-E. Wong (J. H. Lang and M. A. Schmidt)

Sponsorship

CP Clare Corporation

This project continues to explore the application of silicon microfabrication technologies to the development of millimeter-scale relays. The relays under development are intended for use in controlling power, as opposed to switching signals. The potential advantages of these relays include low cost, small size, low power dissipation, and fast switching.

In addition to the development of millimeter-scale relays, this project studies the scientific phenomena of electrical breakdown across small air gaps, and the electrical and mechanical behavior of miniature relay contacts during closing, conduction, and opening. The results of this study will be used to guide the design of the relays.

Gas Phase Catalytic Microreactors

Personnel

S. K. Ajmera, A. J. Franz, M. Gopal and D. Quiram
(K. F. Jensen, M. J. Cima and M. A. Schmidt)

Sponsorship

DARPA

Miniaturization of chemical systems, using microfabrication technology developed for MEMS applications, is a rapidly expanding research area. Our group is exploring potential advantages stemming from carrying out chemical reactions in a microfabricated reactor. Some of the envisioned advantages include enhanced safety, process intensification and increased efficiency, elimination of hazards associated with storage and transport of toxic chemicals by providing point-of-use generation, reduction of process development time, and novel analytical capabilities.

A microreactor for carrying out catalytic reactions with gas phase feeds has been developed. The microreactor consists of a thin membrane capping a channel etched in silicon. Heaters, flow sensors, and temperature sensors are patterned on one side of the membrane, with catalyst deposited on the channel side of the membrane. This reactor design has been successfully used to safely carry out potentially explosive oxidation reactions within flammable regimes. One of the unique aspects of this type of reactor design is the ability to control the reaction temperature, which directly relates to reactor performance. The temperature for highly exothermic partial oxidation reactions can be controlled over a much broader range than conventional reactor designs, enabling operation in novel regimes. Thanks to the heater and reactor design flexibility, these microreactors can also achieve excellent catalyst thermal uniformity, providing additional control over reactor performance.

The microreactor design has also been successfully modified to enable chemical flux through the membrane capping the reactor channel. Palladium membrane microreactors with highly selective hydrogen flux have been developed for selective hydrogenation/dehydrogenation reactions. Palladium membrane reactors offer significant advantages over other types of hydrogenation reactors, but conventional technology is limited by the

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high cost of palladium combined with fabrication methods resulting in thick palladium films. The palladium membrane microreactors take advantage of microfabrication to produce devices with ultra-thin palladium films, greatly increasing reactor efficiency, and possibly decreasing the cost of the technology. The palladium membrane devices have also been used to purify hydrogen, and could find application in fuel cell power generation systems.

Current areas of research attempt to expand the microreactor capabilities and explore use of the microreactors in a variety of applications. Novel microreactor materials of construction and microfabrication methods are under consideration. For example, we are investigating the use of ceramics in microreactor construction to access higher temperature operating regimes and enable operation in harsh chemical environments. In order to use microreactors for chemical synthesis, the ability to operate multiple reactors with multiple fluidic and electronic interconnections is being developed. The use of microreactors for high-speed screening of combinatorial catalyst libraries is under investigation. Finally, we are also exploring the use of microreactors for analytical applications such as calorimetry and kinetic studies.

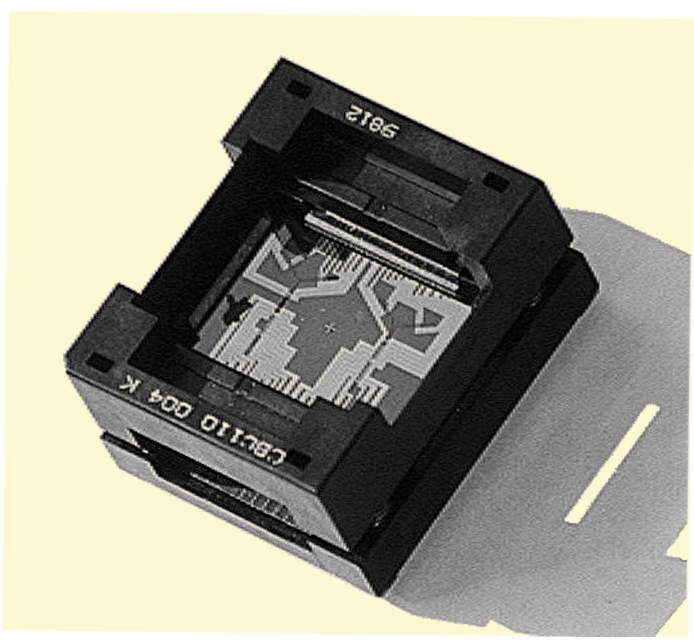

Fig. 17: Two packaged Y-shape gas phase microreactors

Miniaturization and Integration of Photoacoustic Spectroscopy for Use With Microfabricated Reactor Systems

Personnel

S. L. Firebaugh (K. F. Jensen and M. A. Schmidt)

Sponsorship

DARPA, NSF

The integration of chemical analysis would significantly increase the utility of microreactor systems in both research and industrial applications, allowing individual reactor product monitoring which is essential to combinatorial chemistry studies and useful for industrial diagnosis. Of the many potential analysis techniques, photoacoustic spectroscopy has been chosen as a good candidate for integration because of its advantageous scaling properties and its reliance on a microphone as a sensing element.

PhotoAcoustic Spectroscopy (PAS), like other infrared absorption spectroscopy methods, relies on light coupling to the vibrational modes of gas molecules, resulting in absorption bands which identify different gases. Most absorption spectroscopy methods rely on an infrared detector at the end of a sampling region, and the absorption bands are inferred from the transmission spectra. In PAS, the incident light is chopped at an acoustic frequency. If the optical wavelength couples to a vibrational state in the gas, the gas absorbs the light with each pulse, heating up and expanding. The periodic gas expansion can then be detected as an acoustic signal by a microphone.

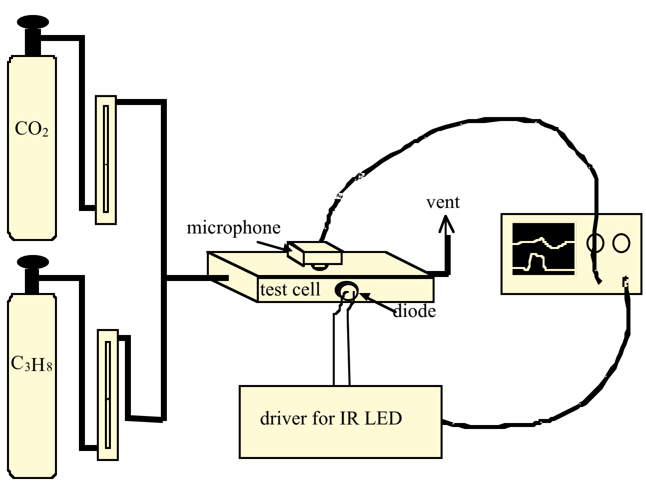

Fig. 18.

All absorption spectroscopy signals are proportional to the path length the light travels through the gas. Consequently, in conventional optical spectroscopy, reducing absorption path length reduces signal levels. In PAS, however, the dependence on path length is negated by an inverse dependence on volume, as reducing volume increases the coupling between temperature and pressure. In addition, heat transfer dominates the photoacoustic response time. At very small dimensions, the advantages of reduced volume are cancelled out by the cell's limited heat capacity. At this point further reductions in size have no effect. At typical acoustic frequencies, the cell diameter at which the response saturates is around 100 mm, which is easily realizable with MEMS technology.

We have conducted experiments with a cell 2 mm in diameter and 1.5 cm long, machined in brass. The sensing element in the macromachined cell is a commercial hearing aide microphone. Using a diode that emits pulses of light in a frequency band common to many organic spectra, we were able to detect varying concentrations of propane in carbon dioxide.

The chief challenge with our approach will be coupling light into the cell, which is a difficulty with any integrated absorption technique. We are currently designing a micromachined cell and investigating the means by which to bring light into the cell. Simultaneously, we are working to reduce the noise of our measurement with the macrofabricated cell with improvements to the test apparatus. We plan to use the macrofabricated cell to demonstrate the advantages of size reduction and to quickly test new design ideas.

Micromachined Chemical Reactors for Liquid and Multi-phase Reactions

Personnel

T. Floyd and M. Losey (K.F. Jensen and M.A. Schmidt)

Sponsorship

DARPA, DuPont and NSF

Microfabrication technology offers the opportunity to manufacture novel chemical reactor designs which could offer improvements in process capability and control and allow the more efficient elucidation of chemical kinetics. The range of applications for microchemical systems has been extended by designing reactors specifically for reactions involving liquid phases.

Micromachined reactor systems would be appropriate for safe production of hazardous specialty chemicals with fast, exothermic reaction rates. Fast, exothermic reactions may be mixing limited. Consequently, the small channels that can be etched using micro-fabrication techniques reduce characteristic mixing times so that maximum conversion of the reactants can be achieved. In macroscopic reactors, exothermic reactions may be subject to thermal runaway. For these systems, it is important to monitor and control the temperature to avoid unsafe operating regimes. Microsystems offer the advantage of low thermal mass, fast control response and advanced temperature sensing using thin-film methods. Furthermore, on-demand, point-of-use production methods would become important for processes with hazardous intermediates due to the safety concerns associated with the storage and transport of these chemicals.

For this work a novel, liquid phase microreactor, was fabricated to address temperature sensing, thermal management and mixing issues identified as important parameters in the production of hazardous specialty chemicals. The reactor design is simple, yet highly integrated with a heat exchanger and thin film temperature sensors. The mixing and heat exchange channels are fabricated using deep-reactive-ion-etching of the substrate of an SOI wafer. The device is capped by anodically bonding Pyrex to both sides of the SOI wafer. The thin film temperature sensors are patterned in the silicon film beneath the mixing and reacting channel. Fast mixing at 10ms and good heat transfer based on an overall heat transfer coefficient of 1445 $W/m^2 {}^oC$ were demonstrated. The established linear resistive response

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of the temperature sensors was confirmed experimentally, and the reactor was shown to operate at 11 psi at the 1.0 ml/min design flow rate.

For the gas-liquid heterogeneous reactions, a continuous flow, packed-bed chemical reactor has been fabricated in silicon using deep-reactive-ion etch technology. The microfluidic channels are formed by etching 300mm into the silicon and using an anodic bond of a Pyrex wafer to cap the channels. A 4 mL volume reaction chamber holds the packing as reactants are fed continuously in a co-current fashion and distributed at the inlet of the bed. In order to promote efficient mixing of the phases and maximize the interfacial contact area, the gas and liquid reactant streams are brought into contact by a series of interleaved, high-aspect ratio (25mm X 300mm) inlet channels. Standard catalyst powders are used to take advantage of their high surface areas and known chemistry. In order to retain the catalyst particles within the reaction channel, a filter was formed near the outlet by micromachining a grating of silicon posts 40mm wide spaced 25mm apart. Catalyst particles consisting of palladium supported on high surface area carbon have been used to perform several classical heterogeneous catalytic hydrogenations. As a class of multiphase reactions, hydrogenations are common throughout the fine chemicals and pharmaceuticals industries, they are exothermic, and often mass transfer limited owing to the limited solubility of hydrogen in most liquid organics. In macro-scale packed-bed reactors, even distribution of both the gas and liquid phases over the catalyst bed is crucial for reactor efficiency. Thermal gradients can limit the life of the catalyst as well as lead to undesired side reactions. As a result, microfabricated chemical reactors may improve reactor performance by taking advantage of high surface to volume ratios to more efficiently control heat and mass transfer.