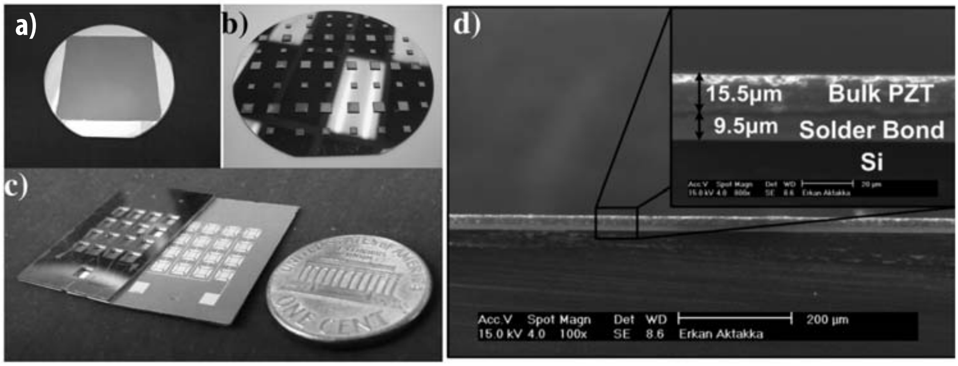
Advanced Materials, Processes, and Packaging

Successful development of MEMS and microsystems requires a number of technologies for their fabrication, assembly, and low-cost packaging. Integration of new materials is especially critical for both sensing and packaging, and dictates cost, environmental compatibility or biocompatibility, long-term reliability, and manufacturing yield of many microsystems. Techniques that are compatible with wafer-level fabrication, low-temperature processing, vacuum and hermetic encapsulation, and standard MEMS post-fabrication approaches are needed. Many challenges remain, particularly with respect to *material diversity* and *package integration*. The research projects include topics in four general areas: wafer-scale bonding and vacuum packaging; assembly, interconnect, and related thin-film technologies; etching and deposition methods for new materials and exploratory applications; and mechanical protection and thermal issues.

Wafer-Level Fabrication of High Performance Piezoelectric MEMS

Ethem Erkan Aktakka, Rebecca L. Peterson, and Khalil Najafi



(a) Bonded and thinned PZT wafer on 4" Si wafer; (b) Die-level polymer bonding of PZT on Si; (c) 4 × 4 array of 2 × 2mm² square diaphragm piezoelectric actuators; and (d) Cross-section of bonded and thinned PZT layer.

Bulk piezoelectric ceramics, unlike deposited piezoelectric thin films, provide greater electromechanical force, structural strength, and charge capacity, which are highly desirable in many MEMS applications including high-force actuators, harsh-environmental sensors, and micropower scavengers. Previous studies for integration of bulk ceramics in MEMS have faced significant challenges, such as non-patternable bond layer, low-bond strength due to high stress and voids in bond layer, or out-diffusion of lead and re-polarization issues due to high-temperature processing. In this study, we have developed low-temperature, fluxless, patternable, and reliable (conductive solder) bonding and (non-conductive polymer) bonding of bulk PZT on Si wafers, both at the die and wafer level (70mm × 70mm), and have demonstrated that bonded PZT wafers/pieces can be thinned down at wafer level to less than 10μm. Different size square d_{31}-mode piezoelectric out-of-plane actuators were designed, and fabricated at wafer level with a 2-mask fabrication process. Resonating square membranes 2mm on a side have been actuated to amplitudes as large as 5μm peak-peak when driven by SV and consuming only 2mW of power. The device performance clearly proves that this technology can be used for fabrication of high-deflection, high-stroke actuators, and sensors for a variety of applications. This project is supported by the Hybrid Insect MEMS (Grant Number N66001-07-1-2006) and the Micro Cryogenic Cooler (Grant Number W31P4Q-06-1-001) Programs of DARPA.

Smart All-Diamond Packaging for WIMS

Zongliang Cao and Dean M. Aslam

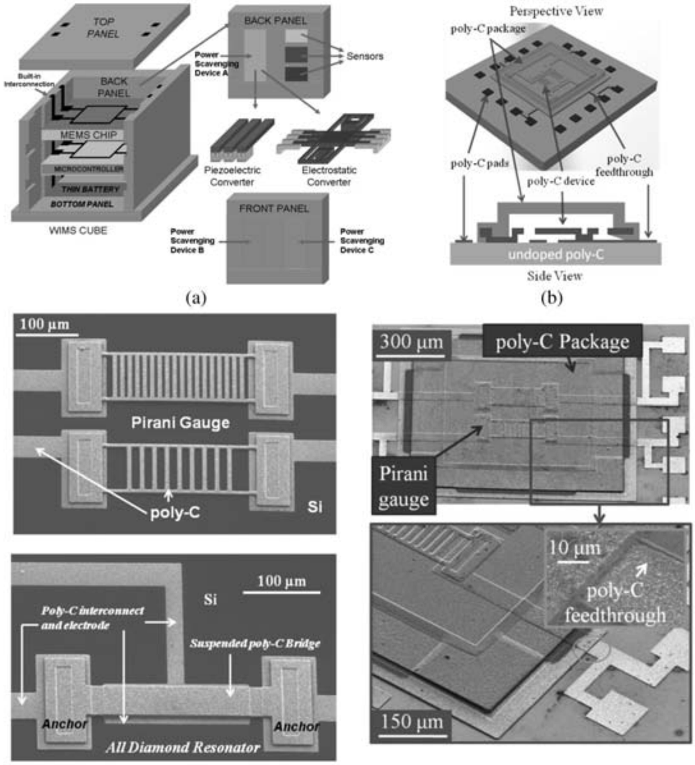


Figure 1 – (a) Models of smart all-diamond WIMS cube; (b) Perspective view and side view of thin-film packaging and all-diamond sensors inside the packaging; (c) All-diamond device inside the thin-film packaging; and (d) All-diamond thin-film packaging.

This project's goals are to develop a smart all-diamond packaging technology where the material used for the packaging, devices, and interconnects is polycrystalline diamond (poly-C) and to put an energy-scavenging device inside the package (Figure 1 (a)). It opens up the possibility of powering MEMS devices from scavenged ambient power.

The research topic that is currently being explored is to integrate different types of sensors (Figure 1 (b, c)) into the thin-film package (Figure 1 (d)). The current study will focus on the design, fabrication, and testing of a smart all-diamond package with built-in interconnects, sensors, and energy-scavenging devices. This project is supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.

Polycrystalline Diamond Micro- and Nanoresonators

Zongliang Cao and Dean M. Aslam

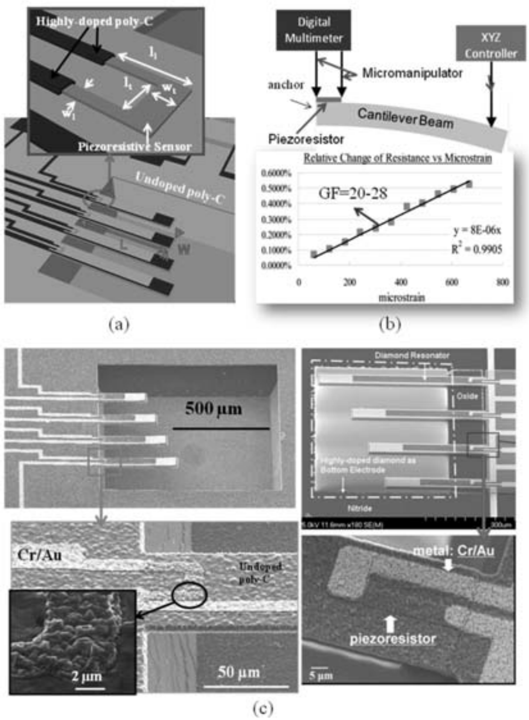
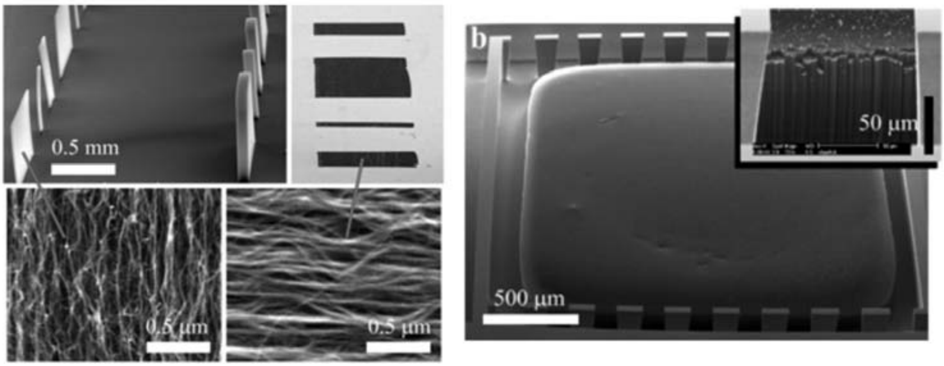


Figure 1 – (a) Schematic diagram of fabricated polycrystalline diamond (poly-C) resonators and piezoresistors; (b) Measurement setup and result for piezoresistive detection characterization; (c) Fabricated structures resonators and piezoresistors.

The p-type polycrystalline diamond (poly-C) films, if used as resonators, can help increase the frequency range for wireless interfaces without making the resonator dimension too small to cause size-related anchor losses. From the application point of view, it is important to build resonator structures with high-quality factor (over 104) and the variable output impedance. This project seeks to (a) design, fabricate, and test poly-C micro- and nanoresonators for sensors and wireless interfaces; and (b) improve quality factor and output impedance using novel resonator devices. The poly-C resonators with integrated poly-C piezoresistors were fabricated out of doped and undoped diamond films grown at 800°C (Figure 1 (a) and (c)). The gauge factor of 20–28 is characterized by beam bending method (Figure 1 (b)). The resonators will also be characterized by electrostatic and piezoelectric actuation in collaboration with Sandia National Labs. The detection techniques include piezoresistive and laser interferometry. This project is supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.

Multifunctional Carbon Nanotube Structures for Environmental and Biomedical Microsystems

Sameh H. Tawfick, Sister Mary Elizabeth Merriam, Rebecca A. Veeneman, Thitiporn Sukaew, Katharine T. M. Beach, Robert J. M. Gordenker, Edward T. Zellers, Kensall D. Wise, and A. John Hart

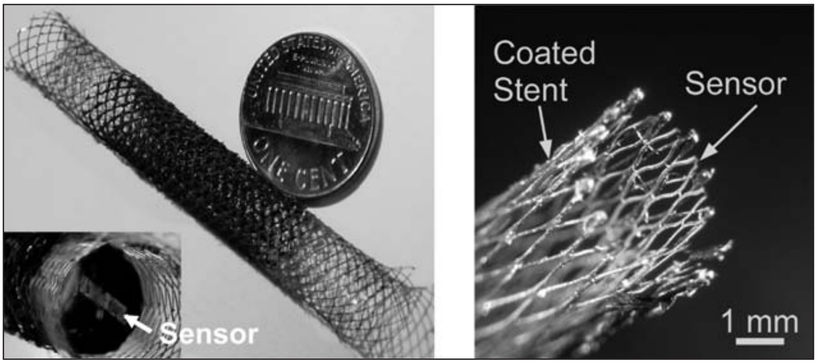


SEM images of CNT forests before and after rolling to create dense horizontal thin films; SEM images of CNT forests grown directly in preconcentrator cavity.

Carbon nanotubes (CNTs) have unique and exceptional mechanical, thermal, electrical, and chemical properties. Our ability to fabricate highly organized CNT assemblies, having critical dimensions ranging from micron to millimeter scales, offers opportunity to harness the properties of CNTs in MEMS devices. Specifically, we aim to create and test CNT structures as patterned vapor preconcentrator adsorbents, as nanoscale columns for on-chip chromatography, and as low-impedance coatings on neural recording and stimulation electrodes. We use a versatile and efficient method for growing CNTs directly on silicon wafer substrates, with a thin-film catalyst Fe/Al_2O_3 (1/10nm) and C_2H_4/H_2 CVD atmosphere. After growth, the CNTs are optionally rolled which transforms the CNTs to a horizontal orientation, or densified using capillary action. Initial results suggest our CNTs can function as highly sensitive adsorbents when grown as forests in the micro-GC cavity; and can significantly lower the site impedance when simply dip-coated onto the neural probe electrodes. Experiments are underway to integrate three-dimensional CNT microstructures by direct growth on the probes; and to investigate the flow resistance through the horizontally aligned CNT films to give high-throughput nanofluidic devices. This project is supported by the National Science Foundation (CMMI-0800213).

Wireless Monitoring of Intraluminal Prostheses

Scott R. Green, Mark T. Richardson, and Yogesh B. Gianchandani



Left – A 1mm x 25mm magnetoelastic ribbon sensor mounted in a commercially available biliary stent (Boston Scientific Wallstent, 8mm x 6cm). The stent has been coated with a thin magnetic layer to bias the sensor. This stent was implanted in a porcine carcass to assess wireless range of the system. Right – A patterned magnetoelastic sensor mounted in a photochemical-machined, coated, self-expanding stent.

This project investigates stents that exploit planar microfabrication technologies and their applications to wireless sensing of blood pressure, flow rate, and tissue accumulation (restenosis). A stent typically has mesh-like walls in a tubular shape, and—once positioned by a catheter—is either expanded radially by the inflation of an angioplasty balloon or is self-expanding upon retraction of a delivery sheath. The vast majority of commercialized metal stents are made by either laser machining of metal tubes, or by braiding metal filaments into a tubular shape. However, these processes limit throughput and are generally incompatible with batch processes typically favored for integrated microsystems. High-throughput patterning of metal microstructures can be achieved utilizing batch-compatible micro-electro-discharge machining (μEDM), which has been applied to manufacture stents that demonstrate better mechanical performance than some commercial stents. Stents with features that facilitate sensor integration can also be fabricated in a batch process using photochemical machining (PCM). This effort has been further extended to develop an inductive antenna stent, or stentenna, and to integrate it with micromachined pressure sensors and electromagnetic flow sensors for coronary applications. The incorporation of resonant magnetoelastic sensors allowing for wireless sensing of viscosity changes and sludge accumulation in biliary applications is also being explored. This project is supported in part by a National Science Foundation Graduate Fellowship, by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866, and by the University of Michigan.

Batch Mode Ultrasonic Micromachining of Ceramics and Application to Sensors and Actuators

Tao Li, Roma Y. Gianchandani, and Yogesh B. Gianchandani

This project is aimed at batch mode ultrasonic micromachining that can transfer lithographic patterns onto hard, brittle, and non-conductive materials such as ceramics (including PZT) and glass with high throughput and resolution. It uses ultrasonically induced vibrations from steel microtools to fabricate microstructures in batch mode onto the workpieces. These microtools are themselves fabricated by batch mode micro electro-discharge machining (μEDM). Recently, the process has been demonstrated on single-crystal quartz which is otherwise difficult to micromachine (Figure 1).

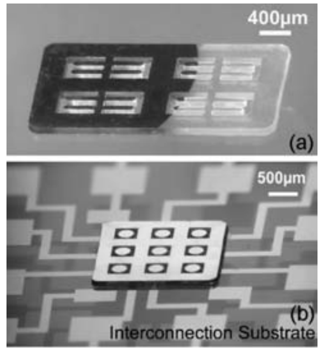


Figure 1 – Batch-fabricated AT-cut quartz crystal microstructures. (a) H-shaped microstructure array; (b) Disk array.

This ultrasonic micromachining process has been applied toward the sensor element of a smart biopsy tool that provides real-time guidance for fine needle aspiration (FNA) biopsy (Figure 2). Discs batch-fabricated from bulk PZT material using the process have been integrated at the tip of a biopsy needle that was shaped by μEDM. Experimental results with porcine tissue demonstrate contrast detection between fat and muscle samples. An empirical tissue contrast model shows an approximately proportional relationship between measured resonant frequency shift and sample acoustic impedance. Sensor elements fabricated by the ultrasonic process have also been integrated with standard CMOS interface circuit chips. This project is supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.

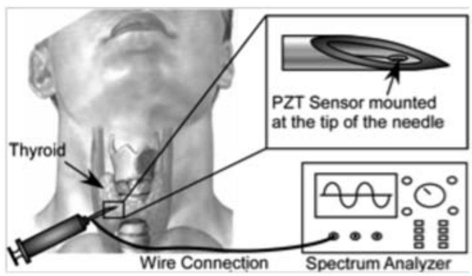
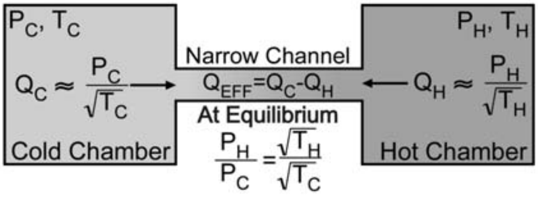
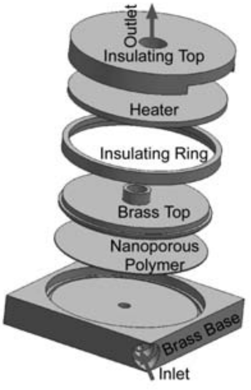


Figure 2 – System diagram for the biopsy tool.

A Thin Nanoporous Polymer Membrane-Based Thermal Transpiration-Driven Motionless Gas Pump

Naveen K. Gupta and Yogesh B. Gianchandani





Left – Two chambers connected with a narrow channel that allows gas flow in free molecular regime—the ratio of pressure at equilibrium is equal to the square root of the ratio of their absolute temperatures. Right – Exploded view of a polymer membrane-based Knudsen pump.

This project focuses on motionless gas pumps that operate on the principle of thermal transpiration. Bulk nanoporous ceramics have a very high density of the nanochannels (>10^{14} channels/cm^2), which transpire gas in unison. We have successfully demonstrated the use of ceramic materials for single-stage and multi-stage Knudsen pumps. Nanoporous polymers may offer even greater promise for high flow rates. Our current designs provide 0.4–1sccm flow at atmospheric pressure, for a pump with approximately 1cm^2 footprint, consuming approximately 1W power. These pumps may offer very high reliability: nanoporous ceramic devices have been tested in excess of 6000 hours for continuous operation. Knudsen pumps for high-vacuum operation are under development. This project has been supported in part by a graduate fellowship from the University of Michigan, and in part by Defense Advanced Research Projects Agency, Microsystems Technology Office.

Locomotion Control of Insects Using Micromachined Thermal Actuators

Karthik Visvanathan, Naveen K. Gupta, and Yogesh B. Gianchandani
Other Investigators: Michel M. Maharbiz (UC-Berkeley)

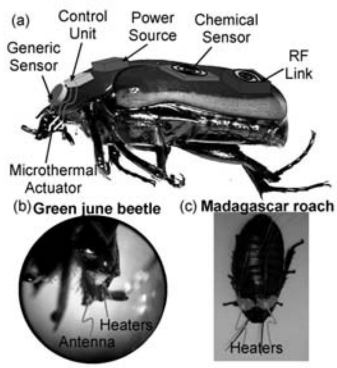


Figure 1 – (a) Concept of instrumented insect; (b) Enlarged side view of the head of the green june beetle with thermal stimulators near the antenna; (c) Photo of Madagascar hissing roach with implanted thermal stimulators.

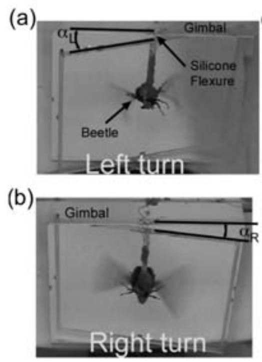


Figure 2 – Photograph of beetle turning towards (a) left and (b) right due to microthermal stimulation near the base of the antennae on right and left side, respectively.

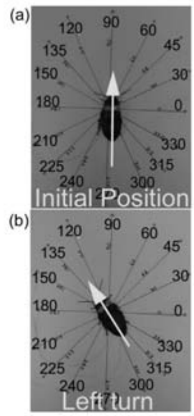
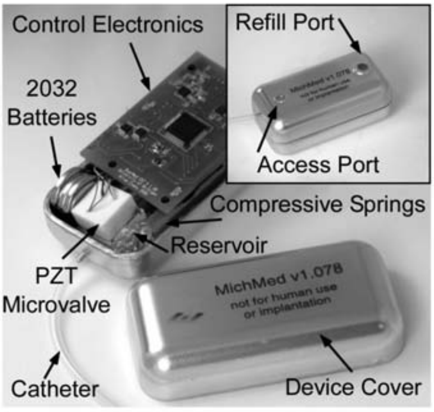


Figure 3 – Photograph of the roach turning towards its left side due to the actuation on the right side.

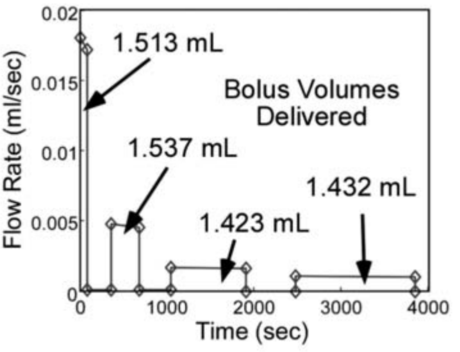
The main focus of this project is to develop micromachined thermal actuators for locomotion control of insects for micro vehicle applications such as military surveillance and environmental monitoring. Experiments were performed using both resistive (nickel), and piezoelectrically driven ultrasonic (PZT-5A) thermal stimulators on green june beetles (GJB) (Cotinis nitida) and Madagascar hissing roaches (Gromphadorhina Portentosa). The stimulators were implanted near the antenna of the beetle and on either side of the thorax of the roaches. Ultrasonic heating was 2× more power efficient, requiring 330–360mW of input power to achieve the 43°C pulses necessary for stimulation. Both stimulators demonstrated the feasibility of locomotion control with a success rate of 80% on GJB and 93.5% on the roaches. The microthermal stimulation resulted in average turn angles of 15–18° and 30–45° on GJB and roaches, respectively. Left and right turns were statistically similar. This project is supported by the Defense Advanced Research Projects Agency (DARPA).

A New Topology for Implantable Intrathecal Drug Delivery Devices

Allan T. Evans, Srinivas Chiravuri, and Yogesh B. Gianchandani



Reservoirs are pressurized with compressive sleeves and regulated by independent microvalves to control drug delivery rates.

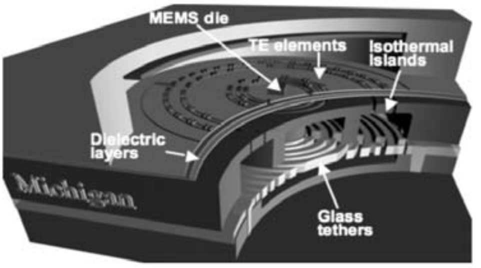


Programmed delivery of 6mL in four boluses of 1.5mL. The total volume delivered was 5.971mL.

The main focus of this project is to develop a dual-chamber drug delivery microsystem that provides regulated flow from two spring-pressurized balloon reservoirs using independent microvalves. In this project, an out-of-plane piezoelectrically driven microvalve scheme is chosen in order to overcome high inlet pressure and low-power constraints with minimum power consumption. Micromachined bulk metal springs (Co-Ni-Cr alloy), with an in-plane spring constant exceeding 300N/m, are used in conjunction with 18.8mL reservoirs, and provide 15kPA pressure when the balloons are fully inflated. A piezoresistive pressure sensor, embedded in the microvalves, monitors reservoir pressure with a sensitivity of 250ppm/kPa, and is used to regulate bolus delivery. In a demonstration of regulated bolus delivery, 1.5mL bolus doses are delivered at different flow rates with minimal total delivery error. This project has been supported by the National Aeronautics and Space Administration (NASA), MICHR, and the University of Michigan Division of Anesthesiology.

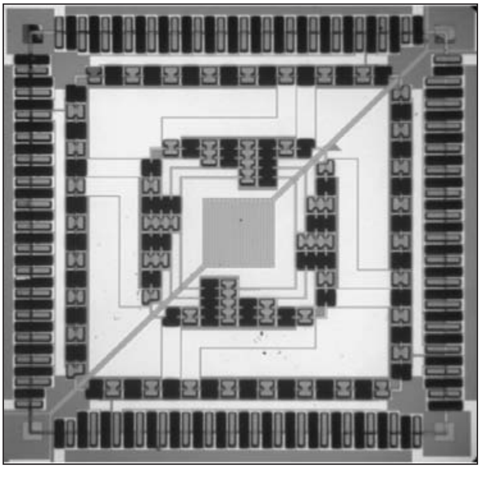
Micro Thermoelectric Cryogenic Cooler for MEMS

Andrew J. Gross, Niloufar Ghafouri, Gi-Suk Hwang, Hengxi Yang, Baoling Huang, Hanseup S. Kim, Rebecca L. Peterson, Ctirad Uher, Massoud Kaviany, and Khalil Najafi



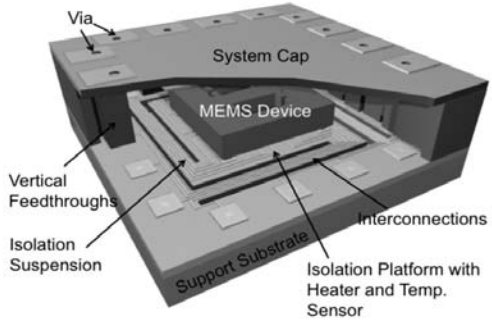
Schematic view of a TE cooler.

A micro thermoelectric cryogenic cooler can have a major impact on critical military, medical, and consumer applications including substantial performance improvement of existing systems such as infrared detectors for military applications. Additionally, the quality factor of MEMS resonators improves drastically as a function of temperature, just as the thermal noise in circuits such as low-noise amplifiers and sensor buffers reduces significantly with temperature. Although not commonly used at the macroscale, thermoelectric cooling becomes appealing at the microscale, where its characteristics of maintenance-free, solid-state operation, and small size are more important than raw efficiency. The ultimate goal of this project is to develop a micro thermoelectric cryogenic cooler capable of achieving a temperature of 160K with heat-lift of 5mW using less than 100mW of power, all in a volume of less than 0.2cc. To achieve the project goal, a multi-stage planar cooler is being implemented to achieve high-temperature differentials at low powers. Recently, the second generation of coolers was fabricated using a thermally isolating design capable of achieving a total thermal resistance greater than 10000K/W. Thin films of Bi_2Te_3 and Sb_2Te_3 with ZT between 0.3 and 0.4 were used as the thermoelectric materials, and the resulting cooler generated temperature differences of 22.3K with input power of 26mW. Future work will focus on improving cooling through reduction of parasitic losses, as well as on vacuum packaging and MEMS device integration. This project is supported by the Micro Cryogenic Cooler Program of DARPA under Grant Number W31P4Q-06-1-001.


Photograph (top view) of a multi-stage thermoelectric cooler.

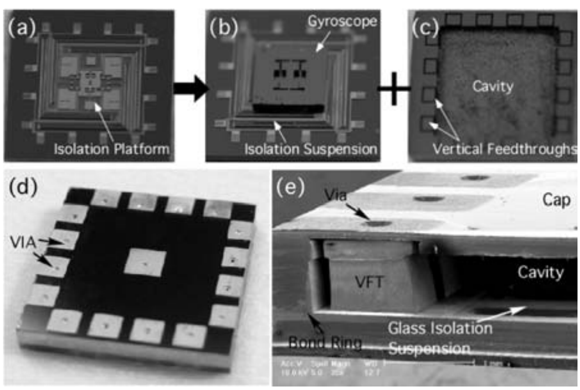
Low-Power Thermal Isolation for Environmentally Resistant Microinstruments

Sang-Hyun Lee, Sangwoo Lee, and Khalil Najafi



Schematic of an environmentally isolated MEMS package.

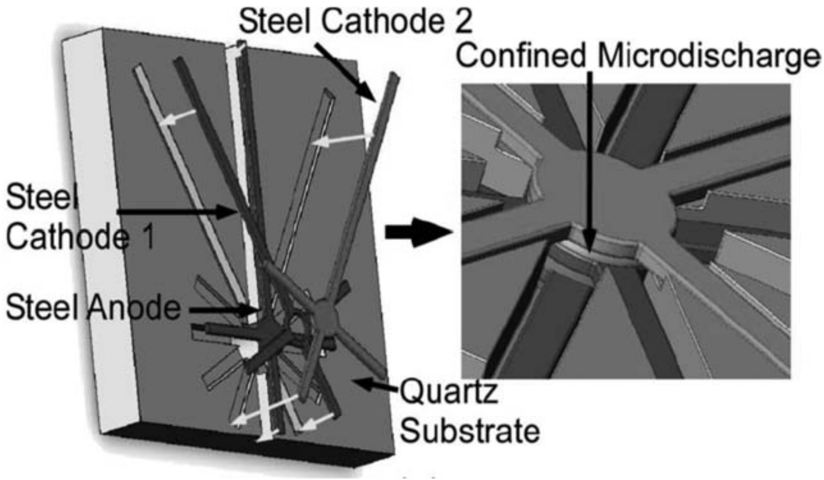
The environment has a profound impact on the performance of precision MEMS. Therefore, it is critical that the environments around the instrument be controlled. The figure shows a view of a generic environmentally isolated platform, which has an isolation suspension made of thin glass. MEMS devices are fabricated on a separate wafer, and batch transferred to the isolation platform. Complete environmental protection is provided by encapsulating the isolation platform and servo-controlling it at a fixed temperature. To achieve low-power consumption, the MEMS device is suspended inside a vacuum package and is supported using suspensions designed to have very high thermal resistance. The package has maintained vacuum-levels of ~6mTorr for >1year. In addition, through our collaborations with Georgia Institute of Technology, micromachined inertial grade gyroscopes have been packaged. The packaged gyroscope shows a high-*Q* mode-matched operation with resolution of 0.01°/sec (*Q*~55,000) at 25°C. With oven-control, the gyroscope is maintained at 80°C, and the drive frequency stays within 0.22ppm/°C while the external temperature varies from −30°C to 70°C. Power consumption for heating the device to 80°C is <33mW when the external temperature is −30°C, and it decreases as the external temperature increases. This project is supported by DARPA's HERMIT Program under Contract Number W31P4Q-04-1-R001.



Photographs of the isolation platform before (a) and after (b) MEMS gyroscope attachment (c) of the vacuum cap wafer and (d) final packaged device. The SEM image in (e) shows a cross section of the finished package.

Microdischarge-Based Pressure Sensors for Harsh Environments

Heidi A. Zipperian, Scott A. Wright, and Yogesh B. Gianchandani

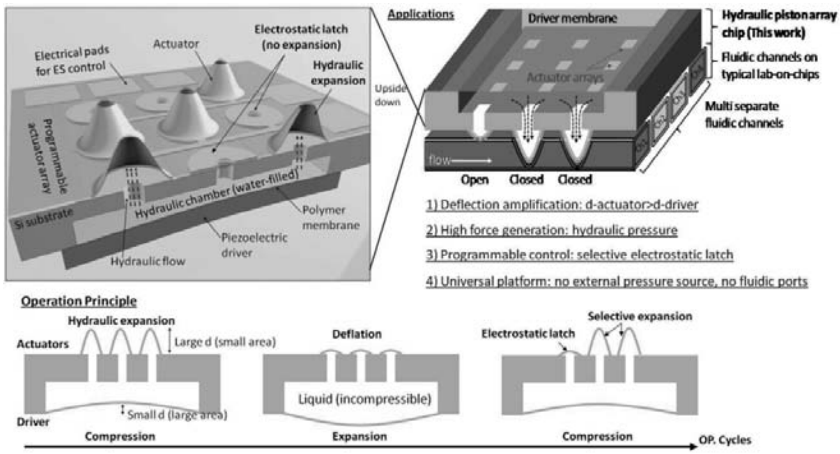


Schematic of a bulk foil sensor with electrodes above a quartz chip, illustrating placement, and the microdischarge chamber during operation.

This project is directed at microdischarge-based pressure sensors intended to operate at elevated pressures and temperatures. The sensors operate by measuring the change, with pressure, in the spatial current distribution of pulsed dc microdischarges between a single anode and two cathodes (or more). The inherently high temperatures of the ions and electrons in the microdischarges make these devices amenable to high-temperature operation. An initial implementation uses 3-D arrays of horizontal bulk metal electrodes embedded in quartz substrates with electrode diameters of 1–2mm and 50–100m interelectrode spacing. These devices were operated in nitrogen over a range of 10–2000Torr, at temperatures as high as 1000°C. The maximum measured sensitivity was 5420ppm/Torr at the low end of the dynamic range and 500ppm/Torr at the high end, while the temperature coefficient of sensitivity ranged from -925 to -550ppm/K. Current efforts are directed at much higher pressures. This project is supported in part by a contract from the Advanced Energy Consortium and by a GAANN Fellowship to Heidi Zipperian.

High-Force and Large-Deflection Electrostatic Hydraulic Microactuators

Hanseup S. Kim and Khalil Najafi



Top – Illustration of a programmable, large-deflection, high-force hydraulic micropiston array for generic lab-on-chip applications. Bottom – Operation principles of hydraulic amplification, electrical actuation, and electrostatic programmability.

High-performance microactuators have become increasingly critical components in many emerging microsystems, for example, to enable liquid manipulation. Despite significant progress, previous lab-on-chip applications still rely on external fluidic sources, such as highly pressurized gas tanks or syringe pumps, to actuate numerous microcomponents. Such dependence has prohibited total system miniaturization and portability. This research addresses the critical hurdle in achieving fully integrated microfluidic systems by developing a new proof-of-concept, all-electrical, microhydraulic actuator array that produces high-actuation displacement/force from electrical signals instead of external pneumatic components. The device consists of flexible membranes that can be individually manipulated by electrostatic latching. Large deflection and force are generated by hydraulic amplification using the back actuation membrane. We demonstrated a 3×3 array platform of $2 \times 2\text{mm}^2$ membranes with maximum deflections of 35, 23, and 11μm when hydraulically driven by piezoelectric actuation at 100, 80, and 60V, respectively. The achieved hydraulic amplification ratios are 3.2, 3, and 2.5, respectively. The array functions up to a frequency of 2Hz, while allowing control over individual actuators by electrostatic latching at 100V. The active device part measures $8.4 \times 8.4 \times 0.65\text{mm}^3$. This project is supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.