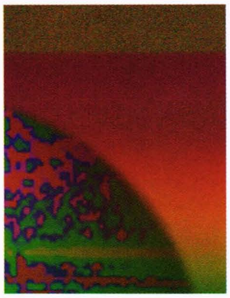


Miniature Sensors Based on Microelectromechanical Systems

Richard C. Benson, John C. Murphy, and Harry K. Charles, Jr.

Miniature sensors have undergone rapid development recently as a result of the extensive design and fabrication infrastructure that exists in the semiconductor industry. These devices are known as microelectromechanical systems and can be used not only to gather information (sensors), but also to process information (microelectronics) and control the local environment (actuators). The Applied Physics Laboratory has initiated a program in this area and is designing, fabricating, and testing devices for selected applications such as measuring magnetic fields, thermal energy, and biological species.

INTRODUCTION

A continuing effort to miniaturize sensors during the past few years has resulted in a significant size reduction to micrometer dimensions. This advance has resulted primarily from the extensive design and fabrication infrastructure within the semiconductor industry for the manufacture of silicon integrated circuits. Silicon micromachining has led to the development of many types of miniature sensors and actuators, commonly known as microelectromechanical systems (MEMS).[1–4] (Refer to the following journals for detailed discussions of MEMS devices: *IEEE Journal of Microelectromechanical Systems*, *Journal of Micromechanics and Microengineering*, and *Sensors and Actuators*.) As the name implies, MEMS devices involve a mechanical response as part of the signal transduction or actuation process.

The primary advantages of MEMS devices are miniaturization, multiplicity, and microelectronics compatibility. Miniaturization results in lighter, smaller, and stiffer (high resonance frequency) structures often designed to exhibit better performance; and, of course, smaller devices can be mounted, embedded, or dispersed more easily than larger devices. Multiplicity refers to the large number of devices and device designs that can be made as a direct result of the parallel fabrication process, which results in lower unit cost and the possibility of increasing overall functionality by interconnecting simple components. Finally, the compatibility with microelectronics enables MEMS fabrication to leverage the extensive infrastructure in the semiconductor industry and allows the integration of electronics on the same chip as the MEMS device.

These advantages manifest themselves in systems that not only gather information (sensors), but also process information (microelectronics) and control the local environment (actuators). Actuators include such things as acceleration sensors for controlling anti-skid braking systems, adjusting liquid or gaseous flow rates, compensating and guiding motion, and deflecting light using adaptive optics.

A variety of devices and applications already exists. Perhaps the most mature and widespread are pressure and acceleration sensors. The acceleration sensor is widely used for triggering the release of an air bag in an automobile crash; such a device is shown in Fig. 1, which demonstrates the extensive integration of electronics on the same chip with the sensor element. Other applications include micromirror arrays used for projection displays (Fig. 2), chemical and biological sensors, room-temperature infrared detectors, magnetometers, embedded sensors for condition monitoring, pumping of fluids (Fig. 3), and various types of actuators (see Fig. 4 for a magnetic micromotor).

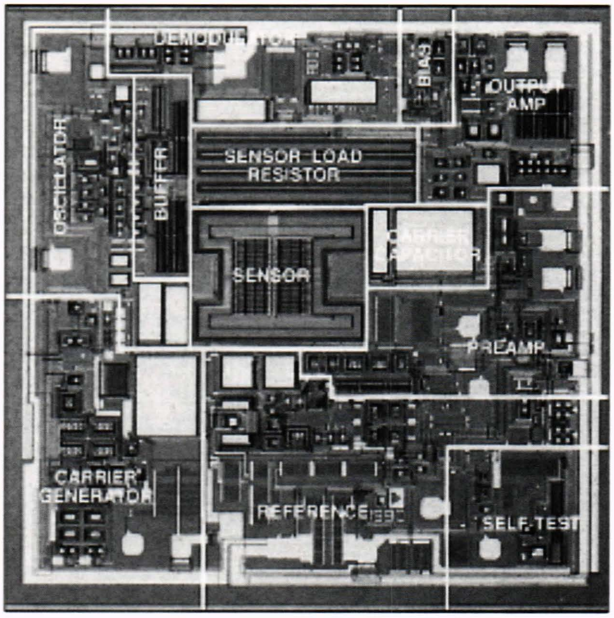


Figure 1. Integrated accelerometer and electronics on a chip. (Reprinted by permission of Analog Devices.)

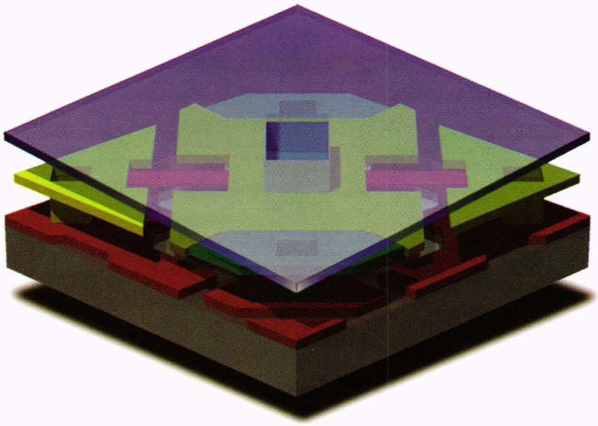


Figure 2. Digital micromirror element. (Reprinted by permission of Texas Instruments.)

DESIGN AND FABRICATION

In typical digital integrated circuits, a single integrated software package of computer-aided design and computer-aided engineering tools is used to design the circuit, model and verify its performance, and then define masks that will be used in the sequential fabrication steps for the various layers on the chip. Unfortunately, no such integrated software package is available for the design of MEMS structures, since mechanical properties and electromechanical modeling are not yet incorporated into the design tools. The approach at APL uses existing computer-aided design tools along with finite-element analysis to model mechanical performance. Results from the testing and evaluation of initial structures are then used to modify the design for subsequent devices.

Once the design has been completed, the devices are fabricated using batch-processing techniques such as

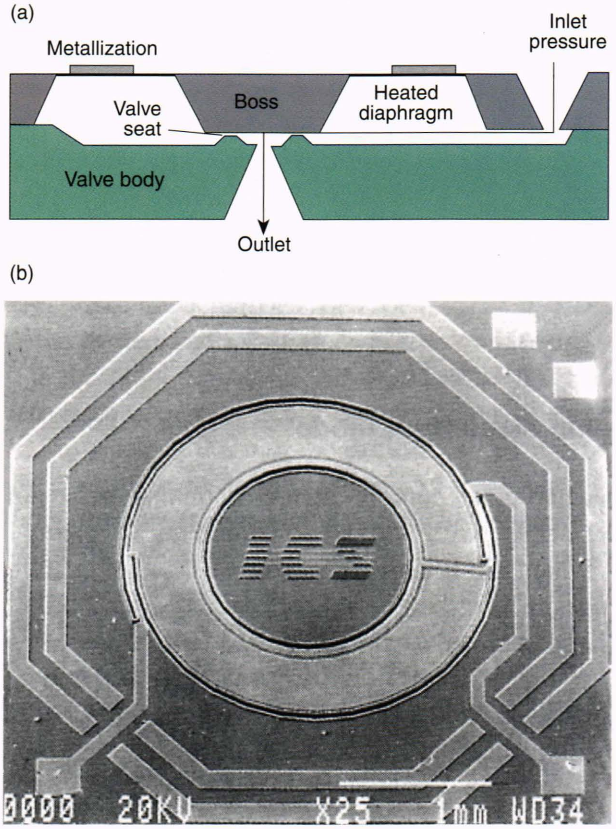


Figure 3. Biometallically driven diaphragm valve. (a) Cross section. (b) Scanning electron micrograph. (Reprinted from Jerman, H., "Electrically-Activated, Normally-Closed Diaphragm Valves," *J. Micromechanics and Microengineering* **4** (4), 211, 1994, by permission. © 1994 Institute of Physics Publishing Ltd.)

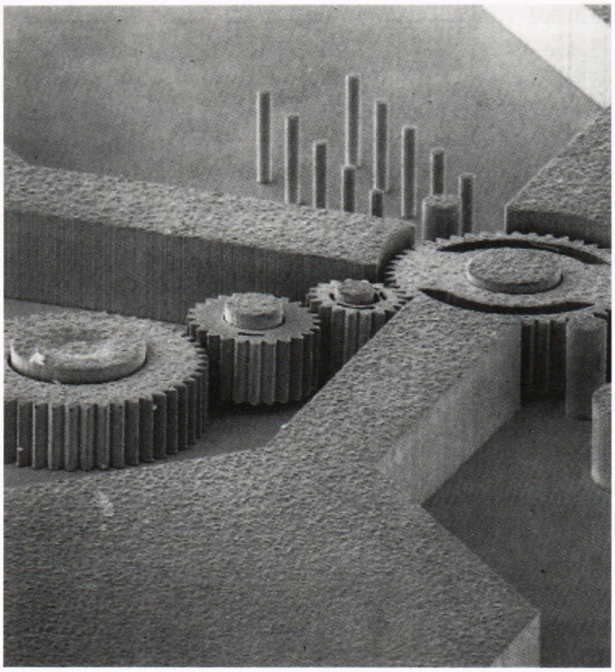


Figure 4. Magnetic micromotor fabricated using the LIGA process defined in the text. (Reprinted from Ref. 1 by permission. © 1994 The Institute of Electrical and Electronics Engineers. Original source: University of Wisconsin at Madison.)

lithography and etching, which result in a low unit cost. The fabrication techniques involve either bulk or surface micromachining for silicon structures, X-ray lithography and electroforming for metal structures having high aspect ratios (thickness to width), and wafer bonding to join separate substrates.

Bulk Micromachining

The oldest fabrication technique is bulk micromachining of silicon, which relies primarily on etching. Early work was based on isotropic etchants that did not allow adequate directional control of the etching process. This limitation was overcome by using anisotropic etchants that preferentially attack one silicon crystallographic plane faster than another. Furthermore, dopants can also be used for selective etching, since heavily doped regions are etched more slowly. Two limitations of traditional bulk micromachining are (1) the aspect ratios of the structures produced are not as high as in other methods, and (2) the structures are not as small.

Surface Micromachining

A more recently developed technique is surface micromachining, which does not involve etching of the silicon substrate. Instead, it uses thin sacrificial layers (usually silicon dioxide) in a multilayer planar structure, which are etched away to leave behind structures that are then separated from the substrate. In the simplest example of surface micromachining, a sacrificial layer of silicon dioxide is deposited or grown on a silicon substrate and patterned using photolithography for selective removal in regions where the mechanical structure is to be attached to the silicon substrate. The layer for the mechanical structure (usually polysilicon) is then deposited and patterned. Finally, the sacrificial layer is etched away to release the polysilicon structure. More complex structures are fabricated using additional layers of materials having the desired properties.

Although surface micromachining is rather flexible for fabricating a wide range of structures, it is generally limited to devices with low profiles and thicknesses (typically a few micrometers). This limitation is due to the thin-film deposition techniques employed in the fabrication process.

X-Ray Lithography and Electroforming

MEMS structures with very high aspect ratios can be fabricated using a process called LIGA, which is a German acronym (LIthographie, Galvanoformung, Abformung) for lithography, electroforming, and molding. Thick photosensitive polymers are deposited onto silicon substrates and exposed to high-energy X rays through masks that have been designed to define the geometry of the microstructure. The exposed regions are dissolved using appropriate chemicals, leaving behind the mold for the microstructure. Metal films are then electroplated to fill the mold, which is subsequently removed to leave the metal microstructure on the substrate. Nonmetallic structures can be fabricated using the metal as the mold, whereby the mold is filled with a polymer, the polymer is cured, and then the metal is dissolved. For structural elements that are to be free of the substrate, surface micromachining is employed along with LIGA.

Microstructures with thicknesses of a few tenths of a millimeter have been fabricated with aspect ratios approaching 300:1 (see Fig. 4). Such geometrical configurations with large thicknesses enable large forces and torques to be generated by the microstructure. The main disadvantage, however, is that specialized X-ray sources are required, usually a synchrotron. Ultraviolet lithographic techniques provide a more accessible process, but at reduced thicknesses and aspect ratios.

Wafer Bonding

Wafer bonding is often used to bond silicon substrates that have been fabricated using one of the aforementioned micromachining methods. Two methods are used: electrostatic bonding and thermal fusion. In electrostatic bonding of silicon to glass, a voltage (typically 1 kV) is applied across the interface at a temperature of 400 to 600°C. Silicon can be bonded to silicon using this method if an intermediate layer of glass is used. Thermal fusion is used to bond silicon to silicon by heating the two wafers in contact with each other to 1100°C. Both bonding methods require clean, highly planar surfaces to achieve bonds that are strong and hermetic. Since high voltages or high temperatures are used, the bonding must be done before adding any electrical circuitry.

Although thin polymer films deposited on a substrate have sometimes been used in devices fabricated via surface micromachining, an alternative approach used at APL involves processing free-standing polymer thin films to produce the desired microstructure. The polymer structures are then assembled with substrates (which may have been micromachined) to achieve the overall device. Some advantages of polymer structures are that greater motion is possible than with silicon and that certain polymers have inherent properties that are very desirable. For example, polyvinyldene difluoride has both piezoelectric and pyroelectric properties that can be exploited for sensor and actuator applications.

MICRODEVICE DEVELOPMENT AND CHARACTERIZATION

Conceptual and detailed designs of MEMS devices are being developed at APL and fabricated at the foundry at the Microelectronics Center of North Carolina, which is supported by the Advanced Research Projects Agency. The major focus has been to design relatively simple structures that, in many cases, can be selectively coated with special materials for particular applications. Our general approach is an iterative one: Design, fabrication, test, and evaluation are used to obtain information that is then used to modify the subsequent design. A parallel effort to this focus on structures is directed at applying APL's existing and extensive background in electronic packaging to MEMS devices.

Various transduction concepts can be used for sensor structures that convert changes in their condition caused by external stimuli into a voltage signal. Transduction concepts include capacitance, piezoelectric effect, pyroelectric effect, electro- and magnetostriction, conductance, tunneling current, and optical methods.

Coated Cantilever Arrays

Cantilever arrays provide a test bed for investigating MEMS devices and applications using a relatively simple structure. The initial devices designed at APL were based on arrays of singly supported polysilicon cantilevers of varying aspect ratios (length to width). The devices are shown in the electron micrographs of Fig. 5. Two basic geometries were chosen: (1) rectangular beams and (2) beams with plates at the end (paddle shaped). Also included in the design were square plates supported at the corners and interdigitated plates whose motion is confined to in-plane vibrations parallel to the base layer. Bond pads and electrical interconnections to the cantilever and insulated base layer were also included in the design.

The devices fabricated in the first run were electrically and mechanically tested. Optical deflection was measured for each structure using both electrical and optical (thermal) excitation. The measured resonance frequencies of the cantilever beams are shown in Fig. 6, which shows that the resonance frequency increases linearly with the inverse of the square of the cantilever length. This result is in agreement with theory.[5,6] The resonance frequencies of corner-supported plates were also determined; the frequency decreased markedly with the width of the plate, as is evident in Fig. 7. The measured resonant and nonresonant responses were in reasonable agreement with predictions from finite-element modeling. The quality factor for the various structures was also determined and was found to decrease markedly as the size of the structure increased. Presumably, this phenomenon is due to damping of the vibration by the ambient air and indicates the need for a detailed understanding of the mechanical properties of microstructures to permit efficient design with a minimum of iteration. This requirement is being met through a collaboration with William Sharpe and Gang Bao of The Johns Hopkins University Department of Mechanical Engineering. Furthermore, information on the capacitance and sheet resistivity of the polysilicon was obtained and used to modify the design in the second chip fabrication run so that the parasitic capacitance is minimized, thereby allowing device motion to be measured capacitively as an option.

The cantilevers and plates are being "personalized" by coating them with thin metallic and nonmetallic layers that will respond to specific external stimuli. Two devices are being developed initially. One is a thermal sensor formed using a deposited layer that has a coefficient of thermal expansion different from the polysilicon cantilever. This device will act like a bimetallic strip and cause the cantilever to bend upon heating.[7] The minimum detectable temperature change, the frequency response, and the device lifetime at mechanical resonance of the cantilever are being investigated. Applications include infrared sensor arrays and chemical sensors for detecting exothermic reactions in the gas and liquid phases. The temperature sensitivity is expected to lie in the microdegree range and to have a bandwidth of 10 kHz or greater. The second device is a micromagnetometer based on the deposition of a magnetostrictive film, such as nickel, that changes dimensions with an applied magnetic field **H**. This sensor should respond in a manner similar to the thermal sensor except that the parameter measured is **H**.

Preliminary estimates of the response of these devices indicate that sensitivities in the nanotesla range may be possible.

The second APL chip fabrication run incorporated refinements in the design of the structures of the first run, along with some new structures such as plates supported in different ways and an electrostatic actuator (Fig. 8). An array of H-shaped torsion plates, similar to the micromirror element depicted schematically in Fig. 2, is shown in Fig. 9. The plate area is approximately 0.325 mm^2, and the H plates cover about 70% of the 3 × 3 device matrix area; coverage areas greater than 90% can be achieved with modified designs. Two designs of the torsion plate array have been developed: (1) all plates are electrically connected in series providing for common deflection of the array structure (beam-diverting mode), and (2) each plate is individually connected, thereby allowing independent addressing of each element in the array (beam-focusing mode). To achieve isolated electrical interconnection

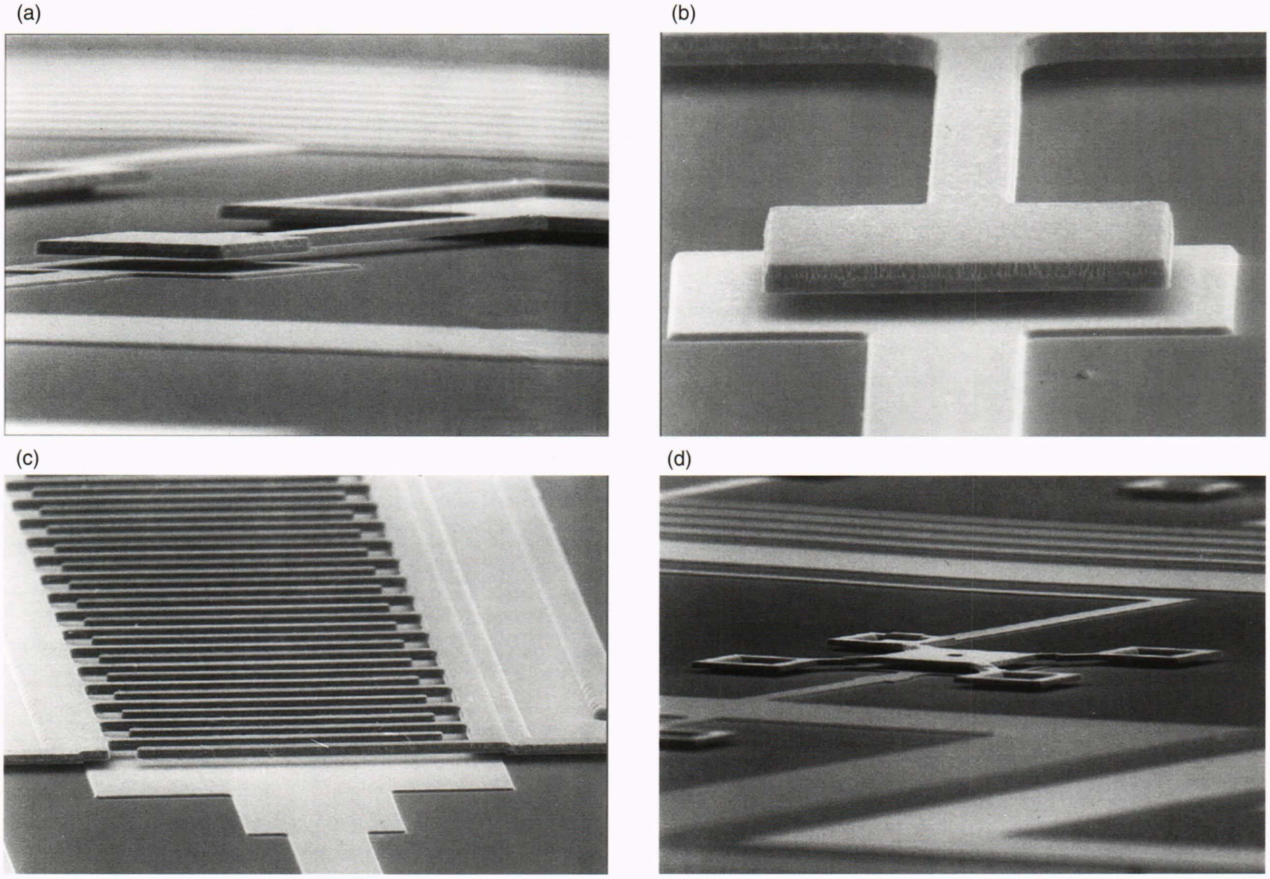


Figure 5. Scanning electron micrographs of MEMS devices in the first APL fabrication run. (a) and (b) Cantilever with paddle end. (c) Interdigitated structure. (d) Corner-supported plate.

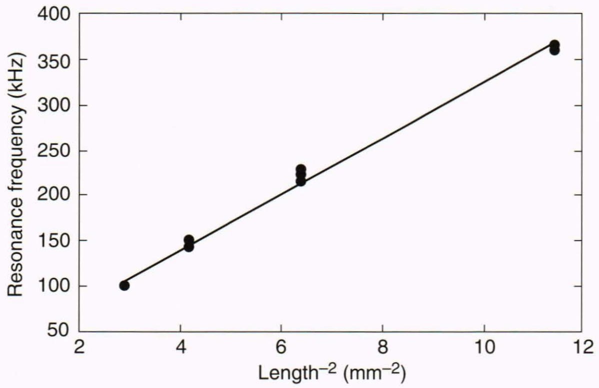


Figure 6. Measured resonance frequencies of cantilever beams using the optical deflection method.

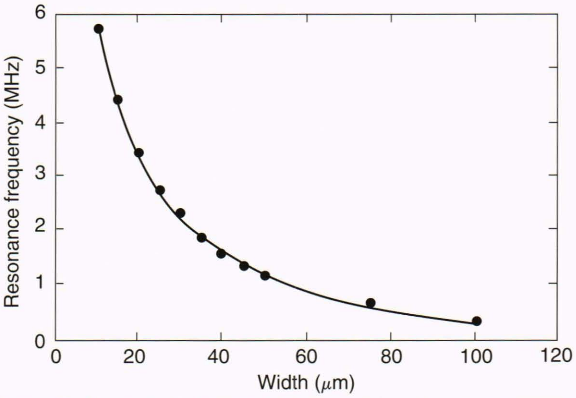
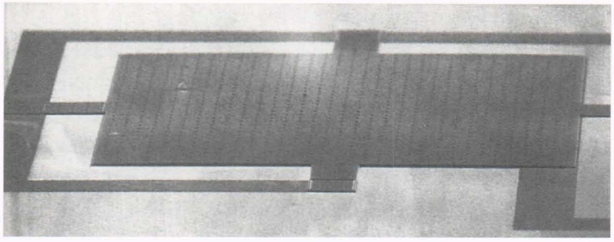


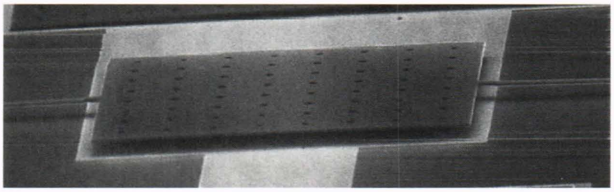
Figure 7. Measured resonance frequencies of corner-supported plates using the optical deflection method.

(a)



(b)

(c)



(d)

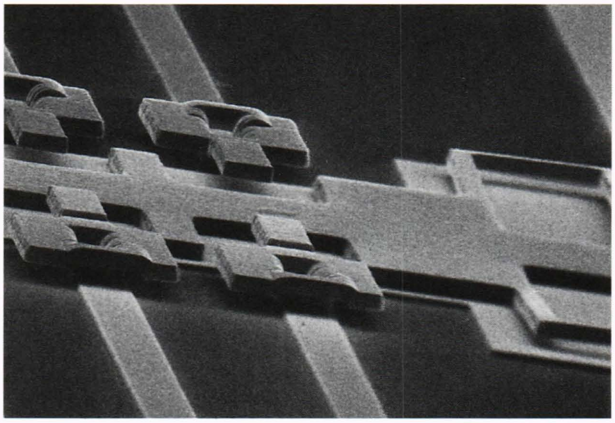


Figure 8. Scanning electron micrographs of MEMS devices in the second APL fabrication run. (a) Square resonator plate. (b) Diagonally supported plate. (c) Edge-supported plate. (d) Electrostatic actuator.

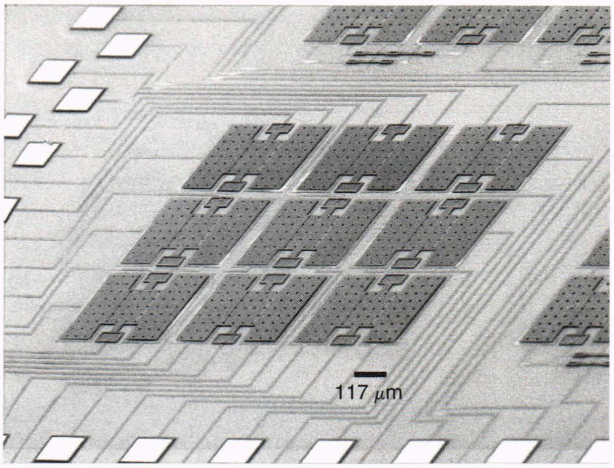


Figure 9. 3 × 3 device array of H-shaped torsion plates.

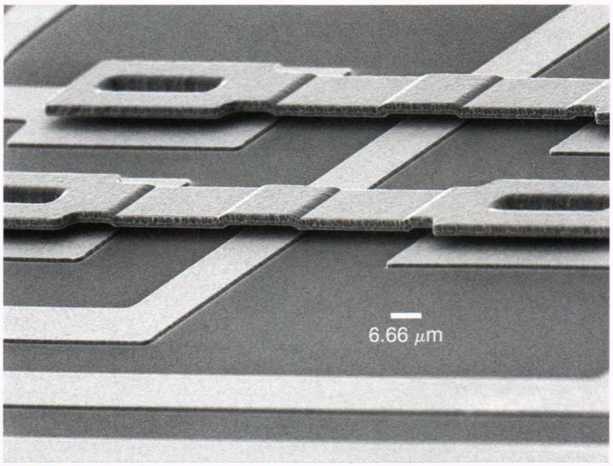


Figure 10. Air bridge crossover for an interconnection structure.

for array elements, a multilevel metallization or single-layer crossover methodology had to be developed using the foundry design rules. Figure 10 illustrates the air bridge crossovers fabricated as part of the array element interconnection lines. The air bridges are typically 40 to 50 μm long and 5 to 10 μm wide, and are suspended about 2 μm over the underlying conductor. To study the reflectivity of the torsion plate arrays, both gold-metallized and unmetallized polysilicon plates were produced.

In parallel with device development, a systematic search is under way for appropriate coating materials for different sensing applications, such as high-specificity chemical sensing of large molecules (in particular, biological species). In this area, APL is collaborating with New Horizons Diagnostics Corp., which has extensive immunoassay and biochemical expertise. Immunoassay methods rely on a specially designed antibody to bind selectively to specific sites on a particular species or organism, and this specificity can be rather good when monoclonal antibodies are used. The antibody is often labeled with another compound, such as a fluorescent dye, to facilitate detection. The merging of MEMS technology with immunoassay methods takes advantage of the large surface-to-volume ratio of MEMS devices and is ideally suited to methods relying on antibodies bound to surfaces. Current work focuses on the selective deposition of antibodies and enzymes on microstructures and the evaluation of stability, selectivity, and range of response.

Although MEMS devices would provide an economical approach for multi-analyte (species) sensors using immunoassay methods, a primary limitation is nonspecific binding of various interfering species by the antibody. Thus, the selectivity of the sensor to the desired analyte is limited in applications where other (nondesired) substances can also bind to the antibody. The standard approach used to overcome this limitation involves the use of arrays followed by extensive signal processing to deconvolute the response from various analytes. APL and New Horizons Diagnostics Corp. have proposed a new approach to this problem by integrating MEMS actuators and sensors for more powerful detection methods, as discussed in the next section.

Integration of MEMS Actuators and Sensors for Biological Detection

As mentioned previously, a limitation of a single-step immunoassay is the nonspecific binding exhibited by antibodies. By integrating MEMS actuators with sensor elements, the analysis can be enhanced via controlled movement of the analyte, enabling coupled chemical reactions to occur. One benefit of this actuator-controlled approach is the ability to perform a type of coherent signal processing in which actuator-initiated reactions allow suppression of interfering background signals. We plan to exploit the fact that unique sites are present on the analyte (antigen) surface that will bind only with specific antibodies. For example, an antibody designed to bind only with the α-site is deposited on one structural element of the device, and another antibody designed to bind only with the β-site is deposited on an adjacent surface. The relative motion of the structural elements can be precisely controlled so that the separation distance (2 μm, for example) matches the separation between the α- and β-sites on the antigen. In this manner, only the antigen of interest will be able to bind with the two device elements. Thus, one of our objectives is to explore the capabilities of MEMS devices in pseudohomogeneous immunoassays and to demonstrate signal detection and enhancement due to coupled reactions on adjacent surfaces. Furthermore, the ability to measure temporal behavior allows inhibitor reactions to be followed, which have higher sensitivity.

This approach of integrating actuators with sensors should lead to a significant advance in analytical capability over other existing methods and, in particular, over the MEMS-based direct detection method discussed earlier. For example, direct detection using immunoassay methods on MEMS cantilevers neither measures the viability of microorganisms nor enables subsequent chemical interactions to be exploited. However, the incorporation of actuator-based controlled motion would enable the bound antigen to be activated and to undergo sequential biochemical steps for viability measurement and enhanced detection specificity, which would minimize false positives. This new concept has broad implications for a wide range of biochemical techniques and should have many applications, such as the detection of biological warfare agents, pathogens in food, and infectious agents in medical facilities.

Polymer Thin Films

The MEMS devices discussed previously are fabricated using the planar silicon technology developed by the microelectronics industry or using X-ray lithography combined with metal deposition. However, as discussed earlier, other routes to the fabrication of microdevice arrays for sensor and actuator applications also take advantage of the parallel fabrication possible using photolithography.

We are developing a system for possible MEMS applications based on the use of polyvinyldene difluoride.[8–10] This polymer has wide application as a membrane in the analysis of biological substances, as a generator and detector of acoustic waves, and as a sensor on the basis of its pyroelectric properties. In terms of MEMS devices, we have shown that free-standing resonant and nonresonant flexural devices (cantilevers and membranes) can be fabricated from polyvinyldene difluoride and driven using optical, electrical, and acoustic sources. In addition, a method of treating the polyvinyldene difluoride to form spatially controlled inhomogeneous structures in the material itself has allowed the flexural motions to be measured by direct voltage methods. This development has also enabled direct excitation of controlled flexure. Concepts for the fabrication and application of arrays of sensors and actuators with submillimeter feature sizes have been developed and provide an alternative to the silicon microdevices.

SUMMARY

MEMS devices have a wide range of application, such as the measurement of physical parameters, the determination of chemical and biological species, and the control of the local environment via integrated sensors and actuators. In the MEMS program at APL, several different structures have been designed, fabricated, and tested. Current work involves the selective deposition of coatings on the structures to develop a MEMS-based thermal sensor, a magnetometer, and biosensors.

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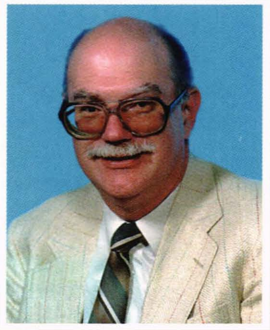

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