MATERIALS AND RELIABILITY ISSUES IN MEMS AND MICROSYSTEMS

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Introduction To Microelectromechanical Systems

The recent evolution in microelectronics of combining electrical and mechanical functions has brought about an exciting new field - microelectromechanical system (MEMS) [1, 2]. Miniature structures developed by new fabrication techniques on semiconductor wafers make possible new devices that have the potential to revolutionize instrumentation and control systems. At the University of Wisconsin (Madison), an air driven microelectromechanical generator has been developed by Henry Guckel. Using parts that are a fraction of the thickness of human hair, a generator was designed giving an output of five volts and weighing under five grams. In separate developments, a team at the University of Michican (Ann Arbor), have built atomic-force microscopes that enable insights into surface science and produce miniature probes for use in advanced prostheses. At the Berkeley Sensor & Actuator Center at the University of California, researchers have built a microgripper capable of handling micron-sized structures. The heart of the gripper is a novel microstructure that consists of interdigitated fingers, or cantilevers, which are activated electrostatically to move the gripper arms. Such a device has potential applications in biomedicine and micro-telerobotics. In the sections that follow, the research issues related to materials and microsystems are discussed. The research problems which must be solved are presented as well as recommendations for research support by industry and federal agencies.

Despite the vast variety of MEMS devices being proposed and fabricated, most of the devices fall into the categories of sensors and actuators, the most important constituents of instrumentation and control systems. The research on MEMS sensors has dated from the late 1960s, and extensive efforts have been made for the fabrication of MEMS sensors to become a mature technology application, as accelerometers which are used in automobile air-bag systems, temperature and pressure flowmeters, and neural microprobes for biomedical study. The promise of the MEMS sensors is that batch fabricated silicon wafers are very low in cost and very sophisticated in feature size, incorporating the use of on-chip circuitry. The micromachined sensors can be produced today with high yield and merged with integrated electronics both in monolithic chips and hybrid multichip assemblies. For some types of sensors, accuracy can be as high as 16 bits and VLSI interface circuits are defined to allow features such as self-testing and digital compensation. One the other hand, consistent progress has also been made in the area of actuators. Microgrippers, piezoelectric micromotors, micropumps, magnetic microactuators, etc. have been successfully fabricated in laboratories. Though some problems remain to be solved in the area of microactuators all of the essential elements of simple MEMS are in place and complete microelectromechanical systems have been proposed with applications ranging from microrobots for security and medical applications to sophisticated positioning systems for assembly tasks at the submillimeter level.

The fabrication techniques used in MEMS are similar to those used by the electronics industry. The microminiatures are made using three micro-fabrication processes -- surface micromachining, bulk micromachining and LIGA processing. These processes employ methods such as photolithography, material deposition, chemical etching, electroplating, and X-ray radiation to shape the mechanical and electronic structures. Although micromachining has been used for over 20 years as a processing technique in the fabrication of sensors, only recently has it been extended to the commercial production of mechanical features from silicon. In the past five years there has been a heightened interest in the use of micromachining technology. Improved etching technologies, deep UV lithography, X-ray lithography for the LIGA process, and ion projection lithography make it possible to attain accuracy for features with high aspect ratios.

While progress has been made in MEMS there are still many techinical challenges which must be solved. In the area of microactuators better driver mechanisms are required. Nonplanar technologies, with assembly techniques at the submillimeter and micron levels are also required. Workstation based design systems along with a database of material, structural, and performance information must be developed. These problems are being addressed and the progress achieved will be discussed in this chapter.

In the sections that follow, applications of MEMS are presented (MEMS Devices section), and several MEMS technologies are discussed (MEMS Technology section). The architecture and current status of CAD tools for MEMS processing simulation and design is also included.

MEMS DEVICES

The MEMS devices developed to date are sensors and actuators. The principles of these MEMS devices are presented including a description of the structures for sensors and actuators.

Sensors

Pressure Sensors

The important category of MEMS devices is that of the silicon pressure sensor which has been identified to have applications in many areas including transportation, health care, and industrial process control. Substantial progress has been made on silicon-based pressure sensors in recent years as a result of advances in etching technologies to form thin silicon membranes. Most of the micromachined silicon pressure sensors contain silicon membranes. Depending on the pressure sensing mechanism they can be classified into two types of devices --piezoresistive sensors and capacitive coupled sensors.

Figure 1 (a) shows the schematic of a peizoresistive sensor which contains a full bridge of diffused resistors to measure stress at four points on the diaphragm and to convert it to an electrical output signal. For a diffused resistor subjected to parallel and perpendicular stress components, $\sigma_{||}, \sigma_{\perp}$ and the resistance change is [3] given in terms of the B-type coefficients, where $B_{||}$ and $B_{\perp}$ are the piezoresistive coefficients parallel and perpendicular to the resistor alignment, depending on the crystal orientation. Thus by arranging the alignment of the diffused resistors in the bridge, two of

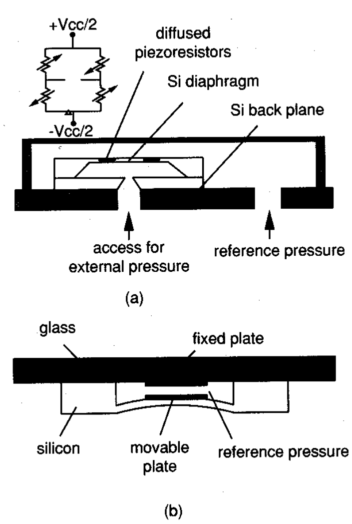

Figure 1 Schematics of (a) a piezoresistive and (b) a capacitive pressure sensor.

them increase in value and the other two decrease in value upon application of the stress. A voltage signal is generated due to the resistance variation and the voltage signal is calibrated to obtain the pressure applied. In the capacitive type sensor shown in Figure 1 (b), the diaphragm is used as a movable plate of a parallel plate capacitor. The pressure is determined from variation of the capacitance of the parallel capacitor.

By varying the diameter and thickness of the silicon diaphragms of 0-200 MPa have been fabricated. The bridge voltages are usually 5 to 10 volts and the sensitivity of silicon pressure sensors vary from 10 mV/kPa for low pressure to 0.001 mV/kPa for high pressure devices. Temperature compensation circuits are also added to the pressure sensor which can result in less than 1% sensitivity for sensors working in the range between 0^oC and 50^oC.

Accelerometers

Several silicon accelerometers based on the diaphragm or cantilever structure from micro-machining have been fabricated [4]. One of the most interesting structures is a cantilever piezo-resistive accelerometer, which is illustrated schematically in Figure 2. The center layer of the glass-silicon-glass sandwich structure, which consists of a mass block and a cantilever, is the heart of the device. Fabrication of the accelerometer is a batch process utilizing standard IC photolithographic and diffusion techniques in addition to the special techniques required to shape the silicon and glass. The silicon element and the top and bottom glass covers are fabricated separately in wafer form and then bonded together. The micro-machining technology will be discussed in more detail in section 3, while the details of the fabrication technology has been reviewed in previous sections and authors.

The cantilever has a p-diffused path which forms a resistor of about 100 Σ /cm . Under acceleration, the mass block exerts stresses on the cantilever. The stresses will induce a change in the resistance of the diffused resistor. The magnitude of the change depends on the crystallographic orientations of the silicon and stress. The variation in the resistance is then detected by an on-wafer Wheatstone bridge circuit. By using of silicon micro-machining technology the entire accelerometer can be made with weight under 0.02 gram and as small as 2 x 3 x 0.6 mm. The sensitivity of such accelerometers can be as low as 0.01 g with accuracy under 1 percent over a range of 100 g, where g is the acceleration of gravity. The accelerometer also has good frequency response with a band-width of 100 Mhz. The performance characteristics of such accelerometers can be varied over a wide range to meet the needs of different applications. One of the most interesting applications, for example, is in the automobile air-bag systems, which a t the present time represents the largest application product.

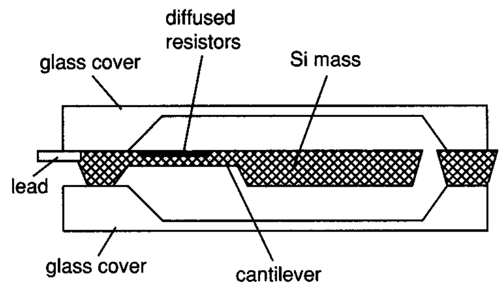

Figure 2 Structure of a cantilever piezoresistive accelerometer.

Shear Stress Sensor

A second example of a MEMS sensor is a floating-element liquid shear stress sensor which has been recently developed at MIT by the group of Martin A. Schmidt [5], and has many potential applications such as flowmeters. The floating-element sensor (120 µm x 140 µm x 5 µm) has been designed for high shear stress (1 - 100 kPas) and high pressure environments (up to 6600 psi) and utilizes a piezoresistive transduction scheme. Figure 3 shows the schematic diagram of the sensor, which consists of a plate (120 µm x 140 µm) and four tetheres (30 µm x 10 µm). The tethers function both as mechanical supports for the plates and a s resistors in the transduction scheme. The plate and the tethers are constructed from a 5 micron thick lightly doped silicon layer and are suspended 1.4 µm above another surface. A flow over the floating-element structure and parallel to the length of the tethers generates a shear stress on top of the suspended plat. Assuming the plat moves as a rigid body, the shear stress forces the suspended plat in the direction of the flow. Two of the tethers experience compressive stresses and the other two tensile stresses. These stresses generate axial strain fields throughout the tether structure, which introduce a change of resistance of the tether due to the piezoresistive properties of single crystalline silicon.

Biosensors and neural probes

Micro-machined structures are emerging as useful instruments in medicine, where precision sensing is critical. An electromechanical sensor array that is small enough to fit inside a blood vessel has been recently developed. The device is inserted into an artery within a catheter that has an inside diameter of 650 microns. It measures the levels of oxygen, carbon dioxide, and PH in the blood. The firm also developed a sensor for monitoring the carbon dioxide and oxygen that a patient inhales during surgery.

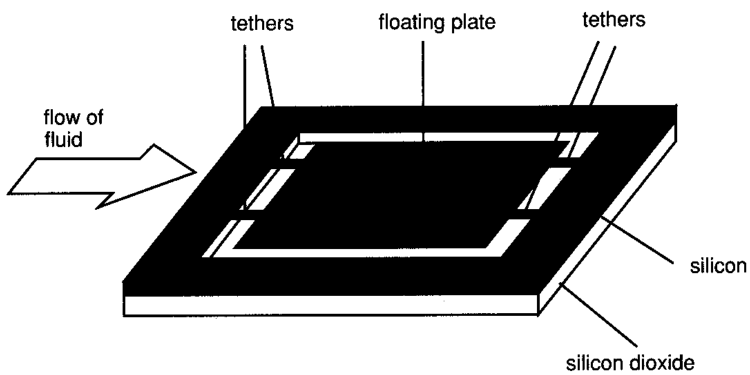

Figure 3 Schematic of a shear stress sensor.

Even more significant to the medical profession may be the development of micro-machined neural probes at the University of Michigan. In the past, sensors have been used to record impulses from one site in the brain at a time. The new neural probe developed is able to record single brain cell activity from 30 sites the brain at the circuit level, which would help scientists learn how to treat neural disorders. Such a probe will also help to develop a neural-electronic interface which will control auditory, visual, and neuromuscular prostheses. The schematic of the neural probe is illustrated in Figure 4.

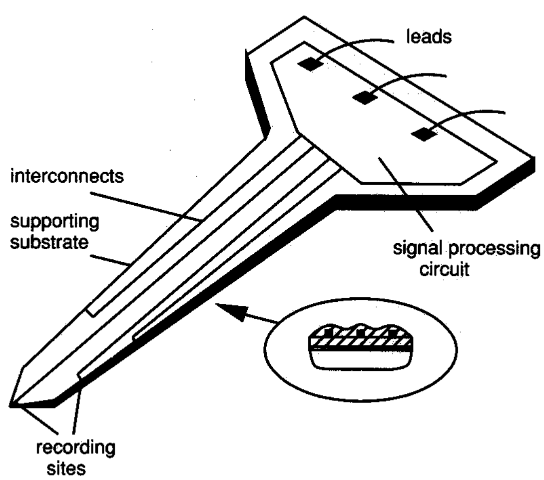

Figure 4 Schematic of a neural probe.

MICROACTUATORS

Microgripper

Recent progress has been made in the MEMS area in the construction of micro- grippers, which are capable of handling micron-sized objects and have applications in biomedicals as well as in micro-robotics. A typical microgripper consists of a fixed closure driver and two movable jaws. The jaws are closed by an electrostatic force from an electrostatic voltage applied across them and the closure driver.

Figure 5 shows the schematic of a microgripper developed at the University of California [6], by Richard S. Muller. The microgripper consists of a silicon die (7 mm x 5 mm), a 1.5 mm long support cantilever, made from boron-doped silicon substrate material, and a 400 micron long polysilicon overhanging gripper extending from the end of the support cantilever.

The silicon die is snapped free along a backside V-groove with a portable vacuum pen. The microgripper and its foundation die is mounted on a positioner and electrically connected using two large contacts that are provided for wire bonding. The microgripper is reported to exert 40 nN of force on the specimen with an applied voltage of 40 V.

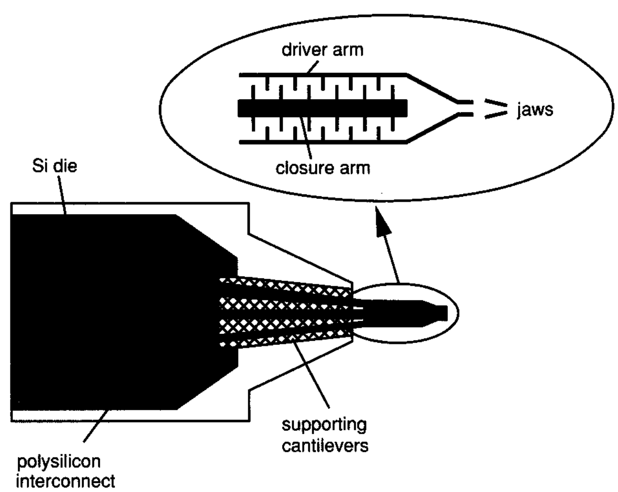

Figure 5 A silicon-fabricated microgripper.

Piezoelectric Micromotors

Another application Of MEMS as a microactuator is micromotors for microbots. Interst in microbots has been driven by recent success in developing intelligence architectures for mobile robots, which can be compiled efficiently into parallel networks on silicon. Various types of micromotors have been fabricated. A silicon center rotor is free to move around a center pole that is bonded to the glass substrate. A stopper is located between the glass substrate and the silicon center pole hub to prevent the rotor from separating from the center pole. During operation the oppositely placed stators are sequentially stepped with applied voltages, an electrostatic force is exerted.

MEMS TECHNOLOGY

Bulk micromachining

Early silicon products were fabricated using bulk micromachining technology with isotropic wet chemical etchants such as hydrofluoric, nitric, and acetic acid mixture. The isotropic etchants have no preferential etch rate to crystal orientation and attack different planes at the same rates. Isotropic etching has problems with etch control, selectability, and precision. Most of the chemicals used today are wet etching anisotropic etchants which selectively etch the < 100 > and < 110 > directions of silicon. Etching in a < II I > direction is much slower than the < I 00 > and < I 10 > directions (typically 50 times slower). The use of anisotropic etchants results in vertical sidewalls for the < I 10 > silicon substrate and at an angle of 54.7' for the < 100 > orientation. Lateral geometries and etch profile can be precisely controlled through anisotropic etching.

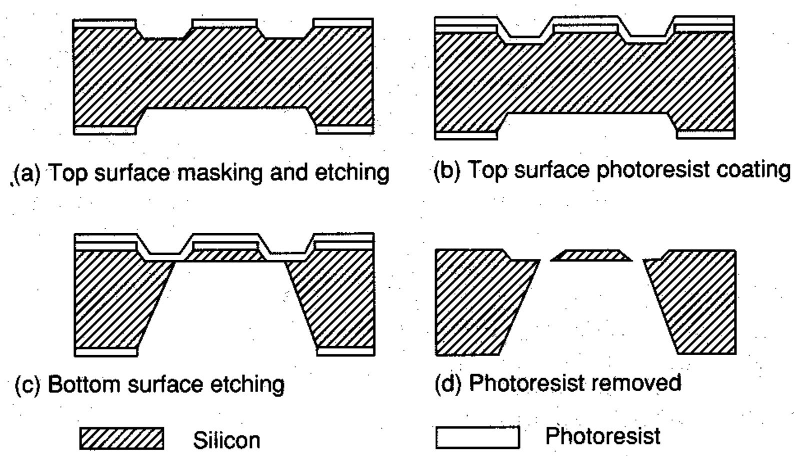

Figure 7 Typical bulk micromachining process.

In a typical surface micromachining process, a silicon wafer is first oxidized in a low pressure chemical vapor deposition (LPCVD) system, which grows silicon dioxide on the surface. Chemicals are then used to etch away parts of the silicon dioxide and to define a required shape. The structure is put through a second LPCVD process, in which a silicon layer grows on top of the silicon dioxide and adheres to the wafer in the areas where silicon dioxide has been etched away. In subsequent etching steps, the shape of the layer is defined, and the film of silicon dioxide is dissolved

In the above technique, the end component is a suspended mass, or a miniature bridge, a geometric feature common to many surface micromachined components. The silicon dioxide is known as the sacrificial layer for the sake of fabricating a suspended structure. In addition, chemical vapor deposition, sputtering and direct evaporation are used to deposit thin films on a chip. Polysilicon, silicon nitride, and tungsten, among other materials, are used for the structures of surface micromachined parts while phosphorus-doped silicon functions as the sacrificial layer. There has been strong interest in polysilicon micromachined parts recently, however some problems still exist. Polysilicon structures of thickness larger than several microns are difficult to fabricate due to the larger intrinsic stress which results from the thicker polysilicon layers.

The advantage of surface micromachining is that the elements are fabricated in preassembled form. This avoids assembling individual mechanical parts by hand. The bulk micromachining technique, in contrast, cannot provide such integrity of micromachined parts. However, the surface micromachining process tends to introduce intrinsic stress as the structure layer is grown on the sacrificial layer. Such stress causes structure warp and limits the thickness of structure to be fabricated with in several microns. Recently an alternative process has been developed for single crystal silicon micromotors [81 based on the combination of both bulk micro- machining and surface micromachining techniques. The new approach utilizes deep etch stop (boron) diffusion and deep trench etching to define the vertical structure of the parts and employs the surface micromachining technique (i.e., sacrificial layer and epilayer growth) to form the joint parts. The new process provides up to 20 microns mechanical structure with higher production yield.

LIGA process

To date, most of the micromachined devices are made using either surface or bulk micromachining. A micromachining technology called the LIGA (an acronym for the German term for lithography, electroforming, and plastic modeling) process is less compatible with integrated circuit manufacturing, but is showing great promise for the development of microstructures. The technique provides well defined, thick microstructures, that have extremely flat and parallel surfaces. These characteristics are particularly useful for fabricating motors, gear trains, and generators having spinning parallel parts that come in contact.

In a typical LIGA process [9], polyamide is first deposited on a silicon wafer as a sacrificial layer. The shape of the layer is then defined by passing ultraviolet light waves through a mask. Next the substrate is covered with a plating base made of a thin film of titanium under a layer of nickel. A photoresist layer over the plating base is deposited, this usually consists of polymethyl methacrylate, a photopolymer similar to Plexiglas.

A mask is placed over the photoresist material and X-rays are radiated through it. The X-rays are powerful enough to penetrate a photopolymer as thick as 300 microns. The X-ray mask is a membrane, typically of silicon nitride, which is only I to 1.5 microns thick. It is mostly transparent to allow - the X-rays through, but gold is deposited in defined regions of the mask to absorb certain X-rays.

X-ray radiation changes the polymer's molecular weight in selected areas, and chemical etchants dissolve away the regions of material that have been exposed. The resulting geometry is a mold into which nickel is electroplated. In subsequent steps, chemicals are used to remove the mold, plating base, and sacrificial layer. Use of a sacrificial layer allows us to fabricate structures that are semi-suspended or free of the substrate. These components are assembled into parts that are attached to the substrate to make interacting microstructures. In a motor, for example, the shaft and the rotor are fully attached parts, while the spinning rotor is machined free of the substrate and mounted to the shaft.

Materials and Reliability Issues

The research issues related to materials must start with the application of "traditional materials" in demanding applications. The application of silicon and GaAs single crystals are many and include mechanical structures (membranes, beams, seismic masses etc) as well as transducer structures (piezoresistor, piezoelectric, photonics). Electrochemical properties are critical such as that of porous silicon and etch stops. Traditional thin film materials are in the form of mechanical structures and chemical structure such as silicon nitride for etching masks, protective layers and silicon oxide sacrificial layers.

New materials, which require concentrated research are: piezoelectric layers (PZT, PLZT, ZNO) and shape memory alloys based on titanium nickle alloys, Other aspects of new materials include low stress silicon nitride, glass layers, doped glass layers with high optical index of amplifying properties, and chemical protective layers. Research in polymers include low stress polymers and glues for enlarged chemical resistance. From a reliability point of view, the compatibility of materials is critical. This area is divided into mechanical effects, chemical effects, thermal effects and optical effects. Mechanical effects include the bimetallic effects and the coupling of external forces into sensitive parts inside the component.

New material analysis techniques are required for microsystems and further analytical is needed for the determination of the mechanical properties of thin films as well as for the chemical properties of protective layers.

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