SOLID-STATE MICROSENSORS AND SMART STRUCTURES

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ABSTRACT

Solid-state microsensors have been recently developed for the measurement of a number of physical and chemical parameters for use in today's instrumentation and control systems. This paper reviews the state-of-the-art in the development of silicon micromachining technologies for the fabrication of silicon microsensors. Micromachining technologies such as bulk silicon micromachining, surface micromachining, and electroplating techniques are first reviewed, followed by a discussion of various thin-film materials used in the implementation of required microstructures. Several examples of silicon microsensors, including a 1024-element silicon tactile imager, and a thermally-based pressure and flow sensor, are presented. Finally, a discussion of potential use of these devices in smart structures and systems is presented.

INTRODUCTION

The development of smart systems and structures for applications that require increasingly improved performance has received much attention and has progressed rapidly recently. Development of new and improved materials and structures that can enhance the electrical, mechanical, thermal, and or magnetic properties of the system is particularly important, and has attracted the attention of researchers around the world to the development of "smart" materials and structures. An area that has especially seen tremendous activity during the past decade is the development of micro electro mechanical (MEM) microsensors and microactuators that interface the external non-electronic environment with the electronic world of microcomputers. Solid-state microsensors are a combination of a number of technologies, including micromachining and microstructure formation, advanced materials and materials deposition technologies, integrated interface circuits, and data acquisition and signal processing techniques, and are currently used in applications ranging from consumer products, automotive, and health care to defense and avionics. These devices are very small (less than a millimeter on a side), are low cost when manufactured in high volumes, are very accurate and stable, and can be realized in large arrays to measure both physical and chemical parameters. Single-crystal silicon and a variety of deposited thin films can be precisely micromachined, with dimensions approaching one micron, using existing technology. Due to their small size, these structures can be used to monitor the mechanical and material properties of various materials and structures in-situ. In addition, by embedding clusters of these microsensors in multi-layered structures, it is possible to obtain detailed in-situ, real-time information on the interfacial and stress/strain profiles of these material systems during both production and use and improve their mechanical performance and lifetime. These miniature sensing clusters can monitor the stress/strain, temperature, vibration, acceleration, and other parameters of interest in various structures.

This paper will first discuss the state-of-the-art in the development of solid-state microsensors and will review the basic fabrication technologies and device structures commonly utilized in their implementation. It will then discuss the formation and utilization of different thin-film materials typically used in fabricating various microstructures. Several examples of solid-state microsensors are then presented. These include a 1024-element high-performance silicon tactile imager for use in robotics, and thermally-based flow and pressure sensors fabricated using surface micromachined microbridge structures. Finally, the paper discusses the potential application of silicon microsensors in smart systems and structures.

MICROFABRICATION TECHNOLOGIES

There is a wide variety of fabrication technologies for micromechanical devices. In general these devices fit into three categories. Bulk micromachined devices are made by carving its parts from a large piece of silicon and bonding them appropriately. Surface micromachined devices are primarily made from deposited thin films. A third category is high aspect ratio devices with height of several hundred microns formed using electroplating and molding of metals and polymers. Each of these techniques is briefly described.

Bulk Micromachining

In bulk silicon micromachining, the microstructures are shaped by etching of a single crystal silicon substrate, as illustrated in Figure 1. For many sensors, the microstructure required is in the form of a diaphragm or beam. With the use of photolithography, an etch mask (typically silicon dioxide or silicon nitride) is defined on the back of the wafer in alignment with patterns on the front surface. The wafer bulk is selectively etched from the back as the final step in the wafer process to form the microstructure while simultaneously performing die separation. However, because most beams or diaphragms of interest are of the order of 1 to 20μm thick, there is a serious problem to be overcome in allowing the batch formation of microstructures controlled to within a fraction of a micron from 400μm to 600μm-thick.
wafers. It is the existence of impurity-based etch-stops in silicon that has allowed micromachining to become a high-yield production process during the past decade. The first and most widely used etch-stop technique (Fig. 1a) is based on the fact that anisotropic etchants do not attack heavily boron-doped (p+) silicon. Thus, a simple boron diffusion introduced from the front of the wafer can be used to create beams and diaphragms. Layers of p+ silicon having thicknesses from 1µm to about 20µm can be formed using this process. Because the boron-doped silicon is in tensile stress, the microstructures are flat and do not buckle; however, because the silicon must be doped above $5 \times 10^{19}$ cm$^{-3}$ to achieve an etch-stop, it is not possible to fabricate circuit elements within this material. To overcome this problem, more lightly-doped silicon epitaxial layers have been used over p+ buried layers (Fig. 1b); however, epitaxial quality is compromised to some extent by the high substrate doping. If instead a voltage can be applied across the sample during the etch, a lightly-doped epitaxial layer of one conductivity type (for example n-type) on a lightly-doped substrate of the opposite type (for example p-type) can be used to form an etch-stop at the epitaxial p-n junction. This electrochemical process permits the formation of high-quality devices but requires the addition of a sensitive bias during the etch. Once the microstructure is formed, thin films are deposited and patterned to perform isolation and transducer functions. Micromechanical devices such as diaphragm pressure sensors and cantilever beam piezoresistive accelerometers are fabricated commercially by this technique. Bulk micromachining techniques have been used for the past 20 years, and are still the most popular.

More complex sensors such as capacitive devices require more than one rigid piece. Bulk samples can be bonded together at the wafer level to form these devices. Many wafer bonding techniques are currently available. Nevertheless, bonding requires wafer alignment and extreme cleanliness of the bonded surfaces to prevent the formation of bubbles and voids. The most common bonding techniques are anodic bonds, low temperature glass bonding, fusion bonding, and metallic seals. Good reviews including other more exotic bonding methods are given in references [1,2].

In anodic bonding [3], the bond is established between a conductive substrate to a sodium-rich glass substrate. The conductive substrate and the glass substrate are placed in intimate contact. The two wafer assembly is heated to a temperature in the range of 350-450°C. This temperature is sufficient to make the sodium ions of the glass mobile. When a voltage of -400-700 V is applied between the two substrates with the cathode being the glass substrate, the sodium ions are depleted from the glass substrate interface creating a shallow ion depletion region about 1µm thick [4-6] with high electric fields in the order of $7 \times 10^6$ V/m. The high field induces a large electrostatic pressure of several atmospheres that brings the substrate and glass [7] into intimate contact. A good bond is established in a matter of minutes. For silicon/glass bonds, the resulting bond is hermetic with bond strength [8] exceeding that of the substrates. Because of the strong fields at the interface, good quality anodic bonds are possible for substrates of poor interface planarity. Since the bond occurs at high temperatures, special attention is needed to avoid bimetallic warping and stray stresses at the interface which can lead to fracture. Ideally, the glass and substrate should have matched thermal expansion coefficients. For bonding to silicon substrates Corning glass 7740 offers the closest match.

Purely thermal bonds are desirable when the high fields used in anodic bonds can adversely affect device performance. In low temperature glass bonding, the bonding interface is coated with a thin layer of low temperature glass. The wafers are then brought together under pressure and the whole assembly is heated to establish the bond. Many different types of glasses have been used including phosphosilicate [1] and borosilicate [9] glasses, sputtered doped [10] glass layers, and spin-on glass slurries [11] and frits [2]. The glass for hermetic sealing can be divided into two types: vitreous and devitrifying. Vitreous glasses melt and flow at the bonding temperature when heated. Devitrifying glasses crystallize at the bond temperature forming a stable film. Low temperature glass provides a weaker bond than electrostatic bonding. Careful processing is needed to avoid the formation of bubbles of trapped gas and voids in the interface.

![Cross-sectional views of bulk-micromachined silicon substrates.](image)

In fusion bonding, wafers are thermally "fused" when in contact at high temperatures in the absence of any intermediate adhesion layers. Fusion bonding of silicon [12] is commonly used for the fabrication of silicon on insulator devices and pressure sensors. First, the wafers are thoroughly cleaned and placed in physical contact with each other on a quartz holder. If the surfaces are flat, the wafers stick together being held by weak Van der Waal forces. The wafer assembly is then transferred to a high temperature furnace to establish the bond. For silicon substrates, the quality of the bond is excellent with no visible interface [13] even in the presence of native oxide layers. Fusion bonding is an attractive method for applications where intermediate layers cause undesirable stresses. However this method requires very high bonding temperatures which do not allow the presence of active devices at the time of bonding. The weak nature of the initial bond makes the quality of the final bond particularly sensitive to the flatness and the cleanliness of the interface. Trapped gas bubbles [14] which lead to partial bonds can be eliminated by high temperature annealing and extreme cleanliness. Organic contaminants have been attributed much of the blame for the spotty nature of the bond.
In reactive metal bonding, a thin layer of metal is sandwiched between layers of silicon. Upon heating, the metal reacts with the silicon surfaces forming an alloy that, when cooled bonds the two parts together. In eutectic alloys, the melting point is lower than the melting point of the pure metal or the silicon. Gold is a commonly used material for eutectic bonding of silicon. Upon heating the gold layer diffuses into the silicon forming an eutectic alloy. For the Au/Si system the eutectic composition is 97.1% Au and 2.85% Si thus the gold is the limiting factor. The temperature required for the formation of the alloy is 363°C. In order to obtain a good quality bond, it is necessary to remove the native oxide from the silicon surface by coating the surfaces with gold or by mechanical scratching. Eutectic bonding is primarily used for die attachments of silicon to gold plated packages, but has been used for wafer bonding of pressure sensors.

**Surface Micromachining**

Surface micromachined sensors are made entirely from thin films. There are several differences and tradeoffs between structures made of bulk and thin film materials. Bulk micromachined devices are enlarged by the propagation of patterns along crystal planes. The die enlargement consumes precious silicon real estate and imposes a limitation on the device count per wafer.

Surface micromachining can utilize any of a number of deposited thin films available in integrated circuit technology, including polycrystalline silicon (polysilicon), silicon nitride, and a number of metallic thin films. To fabricate structures using surface micromachining, a sacrificial film (typically silicon dioxide) is first deposited and patterned on the silicon wafer. The wafer may have undergone other previous processing and may already be coated with silicon nitride. The film for the desired microstructure is next deposited and patterned, and the sacrificial layer is then etched away, undercutting the microstructure and leaving it freely suspended, anchored only where it reached beyond the patterned sacrificial layer to contact the substrate (Fig. 2).

Surface micromachined devices do not have enlargement effects and provide larger device density. The increased throughput reduces the cost of individual sensors and allows for the development of merged integrated sensor/microelectronics systems economically feasible. Surface micromachining permits the fabrication of structurally complex sensors by stacking and patterning layers or “building blocks” of thin films. Free standing and movable parts can be fabricated using sacrificial etching. Although surface micromachining offers increased throughput and complexity, there are important issues that have kept bulk micromachining still in use.

Many sensors are required to work in environments hostile to microstructures. Surface micromachined devices are sensitive to environmental factors such as particulates, humidity, and cleanliness. Special packages are often required to protect the fragile micromechanical elements which can raise the device cost substantially. Often, designers use merged bulk and surface micromachined processes to develop robust inexpensive sensors.

Single crystal materials used in bulk micromachining have well defined properties in contrast to those of amorphous or polycrystalline thin films hence yielding sensors with reproducible characteristics. The thin film microstructure (polycrystalline or amorphous) and its ultimate mechanical properties often depend on specific deposition and post treatment conditions. A tight control over these parameters is necessary for device reproducibility. Many thin materials used in surface micromachining often have internal residual stresses that can affect the mechanical integrity of the finished device. Careful material selection is a requirement to avoid device failure. Surface micromachined sensors made from single crystal silicon offer the most reproducible characteristics. Thin film devices are just emerging in commercial applications.

![Fabrication sequence for surface micromachining](Image)

**High Aspect Ratio Structures**

LIGA (a German acronym for Lithographie, Galvanoformung, Abformung) [15] consists of three basic processing steps: lithography, electroplating, and molding. It begins with coating a thick photoresist ranging from 300µm to more than 500µm in thickness on a substrate with an electrically conductive surface. In order to penetrate the thick resist with well defined sidewalls, lithographic patterning is done with extended exposure to highly collimated X-ray radiation from a synchrotron through an X-ray mask. The desired structures are formed by electroplating metal through the developed photoresist onto the exposed conductive surface of the substrate (Fig. 3). After the photoresist is removed, the metal structure is formed which can be used repeatedly as a mold insert for injection molding to form multiple plastic replica of the original plating base. The plating base replica, in turn, are then used to electroplate many metal structures as the final products. Sacrificial techniques may also be combined with the basic LIGA process to create partially freed, flexure-suspended structures or completely freed devices [16]. The sacrificial layer may be patterned titanium film or polyimide material, which can be removed by selective wet etching following the electroplating and photoresist removal steps.
There are several unique requirements of the LIGA process. The first is the need for X-ray radiation of at least 1 GeV electron energy. The exposure must be sustained for several hours or longer to penetrate the thick resist. The thick photosest, typically polymethyl methacrylate (PMMA), cannot be spun on to the substrate to achieve the 500μm thickness. Instead, in-situ polymerization and casting with well-controlled thickness and minimal stress is feasible.

**THIN FILM MATERIALS**

A variety of thin film materials is available for the construction of mechanical sensors. High quality insulators such as silicon dioxide or silicon nitride, conductors such as aluminum, and semiconductors such as silicon are commonly used. In general, CVD films have the lowest stress and best reproducibly so they are the natural choice when available. Other materials used in microsensors include metals, piezoelectrics, and pyroelectrics [17]. Here we briefly summarize the most commonly used materials.

Thin layers of silicon can be grown on top of insulators. The structure of these films ranges from randomly oriented crystallites (or polycrystalline) to completely amorphous depending on the kinetics of the deposition process. Electrically, polycrystalline silicon has similar properties to bulk silicon for sensing applications. Its piezoresistive coefficient is high [18]; hence it is particularly attractive for stress measurement elements which are separated [19] from the substrate. Dielectrically-isolated polysilicon films are used for high temperature sensing applications.

The residual stress of LPCVD polycrystalline silicon by the pyrolysis of silane can be controlled tightly [20]. Polysilicon grown at 605°C has nearly zero stress [21]. The mechanism of low-stress growth is believed to derive from an amorphous state that recrystallizes in a very reproducible way [22] after annealing. In practice, low stress tensile films are grown between 600-610°C with successive relaxation anneal.

Despite the electrical versatility of this material, its mechanical properties are not fully understood. Several researchers have reported Young modulus ranging from 140 to 210 GPa depending on its polycrystalline microstructure and orientation [23]. These factors are highly dependent on deposition conditions and thermal history. Despite this drawback, many sensors have been implemented with polysilicon, including pressure [24] and acceleration sensors [25].

Unlike polycrystalline films, single-crystal silicon has a well defined structure; hence its mechanical properties are very reproducible. However, single crystal films cannot be chemically grown on non-crystalline substrates. There are a few techniques available to form these films on any substrate.

A common technique [26] involves wafer bonding and back etching. In this procedure, the thickness of the film is defined by a p+ diffused area into the substrate. The wafer is next patterned and anodically bonded to another substrate. The wafer containing the diffused layer is next etched from the back leaving the heavily doped layer intact. Layers of crystalline silicon as thick as 25μm can be fabricated using this process. Contacts to the diffused areas are made by slight overlap in the metallization. Single-crystal films of low doping can be formed using silicon-on-insulator (SOI) techniques [27] and epitaxial growth [28]. In back etched SOI (BESOI), a highly doped buried layer is formed on a wafer by ion implantation. The wafer is next bonded to a substrate wafer coated with an insulator such as silicon dioxide. The top wafer is back etched stopping at the highly implanted region which is subsequently removed by a selective etch. Thin layers of silicon 0.1μm-thick are formed by this process. The thickness can now be increased by subsequent epitaxial growth. Thin layers of single-crystal silicon can also be formed by bonding and grinding techniques [29].
Thin film silicon nitride is an insulating material commonly used in the sensor industry as a mask and a high temperature protective film. Silicon nitride can withstand strong etching solutions such as concentrated HF and KOH and is an excellent diffusion mask for impurity diffusion and ionic contamination. Its high mechanical strength (Young's modulus of 1.1 GPa) makes this film suitable for friction and dust barriers. The nitride films used in semiconductor sensors are amorphous but crystalline forms do exist. Stoichiometric (Si$_3$N$_4$) nitride is a good thermal insulator compared to polysilicon. LPCVD films are the highest quality films available. The deposition takes place in a furnace with dichlorosilane (SiCl$_2$H$_2$) and ammonia (NH$_3$). Stoichiometric nitride films require a gas ratio of SiH$_4$:Cl$_2$:NH$_3$ of 1.3 to 1.4. These films have a large tensile stress (12 GPa); hence only a few hundred nanometers can be grown without excessive warpage and cracking. Silicon rich [30] nitride films are commonly used in semiconductor sensors. The stress of these films can be tightly controlled by adjusting the ratio of dichlorosilane to ammonia. Nearly zero stress films are grown at 835°C and gas flow ratios of 4:1 allowing for the deposition of micron-thick films. The penalty paid is lower resistivity caused by the excess silicon.

Silicon combines chemically with oxygen to form silicon dioxide (SiO$_2$). Thin film silicon dioxide is amorphous and has a lower density than silicon. Silicon dioxide is an excellent electrical and thermal insulator. Its resistivity is high (10$^{12}$ Q-cm), and its thermal conductivity is low (1.4x10$^2$ W/cm°C); hence this material is useful for thermal detectors (bolometers), gas sensors, and flow sensors. Silicon dioxide can be grown or deposited by a number of means. Exposure of silicon surfaces at high temperatures to an oxygen environment grows high quality films of silicon dioxide. This reactive growth process is known as oxidation [31]. During reactive growth, the oxide film expands in volume by about 45%, thus it creates a compressive stress in the silicon underneath. Silicon dioxide films can be deposited by LPCVD using the pyrolytic reaction of silane and oxygen. The stress of oxide films is compressive (1 GPa) and cannot be annealed out; hence silicon dioxide is not an adequate structural film. However, because this film is removed easily from the substrate; it is commonly used as a sacrificial layer.

Organic films are commonly used in sensors. The most common organic films are polyimides. Polyimide films are spin-cast and evaporated onto substrates [32]. This polymer (as with most plastics) swells when it is exposed to a high humidity environment. A number of polyimide based devices have been used for humidity sensors. The mechanical properties of polyimides have been measured [33]. This material is in a tensile state due to the shrinkage at the time of curing. Polyimides are also used as a sacrificial layer that can be removed using an oxygen plasma. Other polymers used in sensors are parylene, hexamethyldisilazane, polystyrene, tetrafluoroethylene, and latex films. Many of these polymers are deposited by plasma polymerization, spin casting, and evaporation. A good survey of the plastic films is given in reference [34]. Active sensing polymers such as piezoelectric polyvinylidifluoride PVDF [35] are also used in pyroelectric and piezoelectric sensors. A common problem observed in polymer materials is the lack of adhesion to the substrate.

**EXAMPLES OF SOLID-STATE SENSORS**

In this section we will present several examples of solid-state silicon microsensors. These examples illustrate different features of today's technology and systems.
Tactile imagers should satisfy a number of requirements for the high-performance end of the applications spectrum. They should offer a resolution of 6-7 bits per pixel, high density with a 1-2mm element spacing to mimic the two point resolution of the human finger tip, and a fast response time of 10-30 mSec. Since these sensors have to operate in difficult environments, they should also be rugged with a high damage threshold, have low hysteresis and drift, and should have a wide operating temperature range with low temperature sensitivity.

A high-density silicon based tactile imager has been developed using a dissolved wafer bulk silicon technology [36]. Figure 4 shows the structure of a single force sensing element in the tactile imager and the overall organization of the tactile imager. Force-sensing capacitors are formed at row-column intersections between selectively-etched metal plates, arranged vertically on the glass substrate along column lines, and horizontal row lines consisting of highly-boron-doped silicon strips. These strips are physically isolated from one another, reducing the coupling between them. High resolution and fast response are thus achieved due to the low stray capacitance of the glass substrate and the low resistance of the highly-boron-doped silicon rows. Figure 4 also shows a block diagram of the data acquisition circuitry. The array has 32 force-sensitive row lines, which are selected by an address signal (A0-A4) and driven by a logic pulse Vp during clock phase φ1, and a force-insensitive dummy row line driven by the opposite clock phase φ2. The column charge amplifiers integrate the difference charge induced on the columns, providing an output voltage pulse V0 whose amplitude is proportional to the crosspoint capacitance change ΔC, which in turn is proportional to the local applied force.

A doubly-supported bridge structure is used for the force sensing elements, as shown in Fig. 4. A force-sensitive capacitor is formed between a metal plate on the glass substrate and a thick silicon center plate fabricated by deep boron diffusion. The thick plate is supported by two thinner beams. Local force applied on the top surface of the center plate deflects the thin beams to change the capacitive gap and hence the cell capacitance. The top surface of the center plate is much lower than the surface of the thin beams, which prevents physical damage to the beams and helps concentrate the applied force on the center plate. A stress-compensated dielectric layer over the silicon capacitor plate prevents electric shorts when excessive force causes the plates to touch, resulting in built-in overrange protection.

The tactile imager is fabricated using a single-sided wafer process, originally developed for an ultraminature pressure sensor [26]. The process uses both silicon and glass processing followed by a silicon-to-glass electrostatic bonding step and subsequent unmasked wafer dissolution. Figure 5 shows the fabrication sequence for the tactile imager. The silicon transducer process starts with a p-type (100) silicon wafer of standard thickness. The wafer is first oxidized and patterned to form silicon bonding islands. These islands are created by etching a recess in the field areas using KOH [36] (Fig. 5(a)). The depth of the recess determines the capacitor plate separation and can be varied from less than 1μm to more than 10μm. Next, a deep boron diffusion is performed on the wafer to define the thick center plate and the bonding islands (Fig. 5(b)). The center plate is typically between 12-15μm thick. A second shallow boron diffusion is then used to define the thin support beams. The thickness of these thin beams can be varied over a large range by changing the time and temperature of the boron diffusion. Finally, a thermal oxide and a LPCVD silicon nitride layer are deposited and patterned to form a stress-compensated interplate dielectric to protect against overforce (Fig. 5(c)).

![Fabrication process sequence for the tactile imager](image)

The glass wafer is patterned with a metal layer to form the lower capacitor plates and the interconnect metal patterns to the silicon islands. Silicon and glass wafers are then electrostatically bonding together by heating them to a temperature of 425°C and applying a voltage of 800-1000V applied between silicon and glass. The silicon row lines are fused to the glass over the bonding island areas and are pulled into contact with the metal lines on the glass in the lead transfer areas by the attractive force of the electrostatic bond, resulting in a low contact-resistance lead transfer from silicon to glass. Finally, the device is placed in an ethylene-diamine-pyrocatechol-water (EDP) etchant, which etches the silicon wafer and stops on the boron p+ layer (Fig. 5(d)) [26]. The overall process requires only four non-critical masking steps for the silicon and results in very high yield.

Figure 6 shows a finished 32 x 32-element tactile imager chip next to a Lincoln penny. Cell capacitors are on 0.5mm centers so that the total area coverage is 1.6cm x 1.6cm, while the overall glass size is 2.2cm x 2.0cm. Figure 7 shows a SEM view of a force sensing element. The dimensions for the thin beam are 300μm x 66μm x 2.5μm and for the thick center plate are 414μm x 254μm x 12.5μm. The lower metallic contact area is 7.15 x 10^4 μm^2 and the capacitor gap is 2.5μm.
The measured sensitivity of the force sensing element is about 0.45 pF/gm, which agrees well with the calculated result of 0.35 pF/gm. This sensitivity is equivalent to a maximum output charge of 4.5 pC for a drive voltage of 10V. The maximum noise charge of the acquisition system, which includes a switched-capacitor charge integrator, is about 19 pC over the temperature range of 0-50°C. Therefore, the system offers a force resolution of over 7 bits. In addition, since the system requires only about 20 μsec per read operation and since the present array is read out with four columns in parallel, the effective element and frame rates are 5 μsec and 5.1 msec, respectively.

Figure 6: Finished tactile imager chip next to a Lincoln penny. The silicon chip measures 1.8 cm x 1.7 cm, while overall glass size is 2.2 cm x 2.0 cm.

Thermal Sensors and Sources

The resistance of heated elements is an easily and precisely measurable parameter; hence thermal devices are widely used as microsensor elements. Figure 8 shows a schematic of a thermally actuated microbridge. This structure consists of a conductive doubly suspended beam that is thermally isolated from its substrate and embedded in a gas or other fluid. The temperature of the bridge is increased above that of the substrate by ohmic heating. The device resistance itself is a function of its average temperature. The temperature of the bridge and its resistance are influenced by external factors of the fluid. Microbridges can sense fluid flow and pressure changes since both of these affect the heat balance of the device. Figure 9 shows a SEM photo of a flow sensing microbridge [37]. Currently, flow sensors for mass flow controllers are manufactured using bridge structures. The same microbridge structure can sense changes in pressure. The thermal heat transfer from a suspended microbridge through a gas is dependent on the gas pressure. Therefore, by measuring the filament temperature and current/voltage characteristics it is possible to detect absolute gas pressure. In addition, microbridge structures are attractive devices for integration with on-chip circuitry. The photograph of Figure 10 shows a polysilicon microbridge-based pressure sensor with on-chip biasing and A/D conversion [38]. The microbridge is located on the top left hand side of the photograph and is about 500 μm long, 1 μm thick, and 3 μm wide.

By encapsulating the structure in a vacuum shell as shown in the process flow of Figure 11, the heated beam can act as an efficient source of black body radiation. Miniaturized broadband light sources are very useful in chemical recognition analysis. Power efficiencies of 5% and peak wavelength of 2.5 μm were demonstrated in this device [39].

Figure 7: SEM view of a tactile imaging cell, showing the force transducer, support islands, thin beam (2.5 μm) and thick center plate (15 μm).

Figure 8: Structure of a silicon microbridge used in thermal microsensors for the measurement of parameters such as gas flow and pressure.

Thermally-Based Silicon Gas Sensor

Gas sensors are in high demand for many applications, including automotive, medical, and process control, and thus,
a significant amount of research has been concentrated on them during the past decade. However, substantial performance problems remain unresolved, the most important of which involve slow response, low sensitivity, poor selectivity, long-term drift, and high-input power. Recently, a conductivity-type gas sensor based on the use of ultra-thin metal films on selectively-formed dielectric windows has been reported [38, 39]. Early results indicate that such devices have great potential and are capable of overcoming many of the current problems. For instance, fast detection of sub-ppm oxygen levels in CF₄ has been demonstrated with negligible drift and hysteresis [40].

Figure 9: SEM view of a polysilicon microbridge. The bridge is about 2µm thick, 5µm wide, and several hundred microns long.

The cross-section and top view of the basic structure of the single-element gas detector are shown in Figure 12, while, a photograph of a gas detector chip is shown in Figure 13. This sensor is a conductivity-type gas sensor based on the use of ultra-thin metal films on selectively-formed dielectric windows, and relies on the dielectric window to provide high thermal isolation between the thin sensing film and the silicon chip rim, minimizing the amount of input power required by the detector for a given operating temperature. Such detectors can produce window temperatures in excess of 1300°C, well above those required for most gas sensing applications (i.e. 250-500°C). The conductance of the thin film depends on the types and quantities of gases present, gas adsorption, window temperature, and possible surface reactions. The response to gas is measured as an adsorption-induced thin-film resistance change. Here surface adsorption dominates over bulk effects in determining film conductivity and response time. Surface adsorption is normally reversible by applying higher temperatures.

Thin films are highly sensitive to some gases and inert to some others. Therefore, a multi-element gas analyzer, having a number of different thin film detectors, has been developed to both overcome the drawbacks of the original gas detectors and to improve selectivity and specificity in analyzing gaseous mixtures [41]. A custom-designed integrated circuit chip allows the independent control and operation of each of the gas sensing chips. Each sensor can be heated to a temperature above 1000°C, while the impedance of the thin film can be measured over the range 5Ω to 1MegΩ with an 8-bit resolution. These sensors have been shown to measure gas concentration to better than 1 ppm [40,41].

Figure 10: Photograph of an integrated thermally-based pressure sensor. The pressure sensor is made up of a microbridge that can be heated to a several hundred degrees above ambient. Heat loss in the microbridge to the outside ambient is a function of the ambient pressure. On-chip circuitry is integrated to control the heater temperature and generate a digital signal. The chip measures 4x4.5 mm².

Figure 11: Process flow for a surface micromachined polysilicon microbridge encapsulated in a shell. These microbridge devices have been used as flow and pressure sensors, and as black body radiation sources.
acceleration, vibration, gas concentration, humidity, position, force, temperature, and strain. Ideally, the measurement unit should be capable of producing a digital output that is compensated for secondary parameters such as temperature.

Our group at the University of Michigan is developing a multi-sensor microinstrumentation sensing cluster for environmental sensing, as shown in Figure 14. The cluster consists of a number of sensor front ends each of which contain a number of sensors and their associated on-chip interface circuitry. These sensor front ends can measure several parameters of interest, including ambient and barometric pressure, acceleration in all three axes, rotation, humidity, temperature, gas concentration, sound, and position. The sensor front ends are connected to a central microprocessor and microcontroller unit through a standard bus [41] developed for these systems. The central microcontroller unit converts all sensor data into a digital format, maintains full control over data transmission on the bus, performs sensor data compensation, manages electrical power distribution and consumption for the entire system, and transmits sensor data over a wireless telemetry link to the outside world. The entire cluster will have an average power dissipation of less than 100μW and occupies a volume of less than 5 cubic centimeters. Microinstrumentation clusters like this have several applications in environmental monitoring, in automotive, in avionics, and in consumer appliances.

In addition to their use in smart sensing systems, solid-state microsensors and microactuators also have important application in smart structures. By embedding sensors and actuators in various structures, it is possible to track and monitor the overall characteristics of the system. For example, it is desirable to continuously monitor the mechanical stresses and strains, and the extreme temperatures that various physical structures, such as bridges and roads, undergo during their lifetime. It is possible to embed sensor clusters into these structures at the time of their construction and obtain measured data using wireless techniques from these embedded sensing systems. A second example involves monitoring of structural integrity of aircraft or space vehicle. It is desirable to build a number of sensors into the vehicle body, such as the wings, in order to monitor parameters such as fluid flow, pressure, temperature, and vibration. This information is necessary to prevent failures and to improve the performance of the system through closed loop control. Embedded arrays of sensors and actuators are also being explored by several groups for development of "artificial muscle" [42] and "smart skins" capable of eliminating turbulence [43]. Micromechanical devices will play a major role in these and future applications of smart materials.

**FUTURE TRENDS AND CONCLUSIONS**

Solid-state microsensors offer a number of advantages in terms of improved stability, reliability, accuracy, speed, size, and cost in many application areas. While the main commercial market up to now has been for individual sensors, such as pressure sensors and accelerometers used in automobiles, it is strongly believed that integrated sensors have potential application in smart systems and structures. Many emerging instrumentation and control systems require the accurate measurement of a number of physical and chemical parameters. Parameters of interest include pressure,
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