

Surface Micromachined Sensors and Actuators

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Abstract

A description of a three-level mechanical polysilicon surface-micromachining technology including a discussion of the advantages of this level of process complexity is presented. This technology is capable of forming mechanical elements ranging from simple cantilevered beams to complex, interconnected, interactive, microactuated micromechanisms. The inclusion of a third deposited layer of mechanical polysilicon greatly extends the degree of complexity available for micromechanism design. Additional features of the Sandia three-level process include the use of Chemical-Mechanical Polishing (CMP) for planarization, and the integration of micromechanics with the Sandia CMOS circuit process. The latter effort includes a CMOS-first, tungsten metallization process to allow the CMOS electronics to withstand high-temperature micromechanical processing. Alternatively, a novel micromechanics-first approach wherein the micromechanical devices are processed first in a well below the surface of the CMOS starting material followed by the standard, aluminum metallization CMOS process is also being pursued.

Following the description of the polysilicon surface micromachining are examples of the major sensor and actuator projects based on this technology at the Microelectronics Development Laboratory (MDL) at Sandia National Laboratories. Efforts at the MDL are concentrated in the technology of surface micromachining due to the availability of and compatibility with standard CMOS processes.

The primary sensors discussed are a silicon nitride membrane pressure sensor, hot polysilicon filaments for calorimetric gas sensing, and a smart hydrogen sensor. Examples of actuation mechanisms coupled to external devices are also presented. These actuators utilize the three-level process (plus an additional passive level) and employ either surface tension or electrostatic forces.

1. Background

The Microelectronics Development Laboratory (MDL) at Sandia National Laboratories is a 30,000 square foot, class 1 semiconductor fabrication facility located in Albuquerque, NM. Its various missions can be categorized into four technology areas: 1. Sub-micron, high-density CMOS, 2. Radiation-hardened nonvolatile memories, 3. Smart Sensors, and 4. Micromechanical sensors and actuators. This paper discusses the development of polysilicon surface micromachining and how this technology has impacted the laboratory's development efforts in smart sensors, actuators, and CMOS.

The MDL is a modern, well-equipped CMOS fabrication facility with both 2 micron and 0.5 micron CMOS technologies. The facility has been adapted to enable the advancement of other technologies in addition to the continued development of sub-micron CMOS. These technologies benefit from the wide variety of equipment and processes in existence to support the baseline CMOS, however these technologies must also maintain a degree of compatibility with CMOS

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manufacturing processes. In particular, a primary concern is the issue of CMOS process contamination.

In the general area of micromechanics, the MDL has development projects in both surface and bulk micromachining. Because bulk micromachining does not take full advantage of the capabilities of the facility, the majority of the work underway at the MDL is being performed in surface-micromachining. As examples of the available capabilities, both undoped and in-situ phosphorus-doped polysilicon films as well as low-stress silicon nitride can be deposited for use as structural layers. A variety of glasses (for use as sacrificial layers) such as TEOS, PSG, and BPSG can be deposited by both conventional chemical vapor deposition (CVD) and plasma-enhanced CVD (PECVD). Both wet and dry etch processes are available for patterning of these films. Additional materials such as tungsten and copper can be deposited in either blanket or selective CVD processes.

2. Polysilicon Surface Micromachining Technology

In this section, a cursory introduction to polysilicon surface micromachining is given since Howe and Muller[1] provide a basic definition for surface micromachining and earlier Sandia work [2] provides a detailed description of the Sandia three-level process. Following this introduction is an argument for the extension to a three-level process and some of the recent advances to the process which promise to further increase its utility. This section then leads into the discussion of integration of this micromachining technology with on-chip CMOS electronics.

Surface micromachining uses the planar fabrication techniques common to the microelectronic circuit fabrication industry to manufacture micromechanical devices. The standard building-block process consists of depositing and photolithographically patterning alternate layers of low-stress polycrystalline silicon and sacrificial silicon dioxide. As shown in Fig. 1, vias etched through the sacrificial layers provide anchor points between the mechanical layers and to the substrate. At the completion of the process, the sacrificial layers, as their name suggests, are selectively etched away in hydrofluoric acid (HF), which does not attack the silicon layers. The result is a construction system consisting of one layer of polysilicon which provides electrical interconnection and one or more independent layers of mechanical polysilicon which can be used to form mechanical elements ranging from a simple cantilevered beam to complex systems of springs, linkages, mass elements and joints. Because the entire process is based on standard integrated-circuit fabrication technology, hundreds to thousands of devices can be batch-fabricated on a single six-inch silicon substrate.

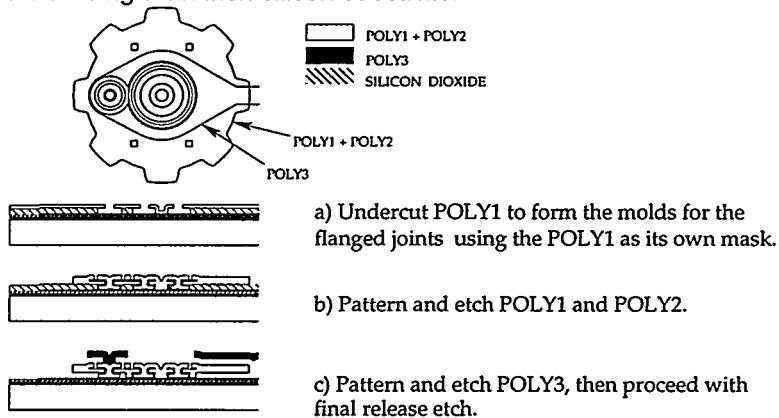


Fig. 1 This example for surface micromachining is taken from the Sandia microengine [2] discussed in section 4. Schematic cross-sections through essential elements of the gear and joints taken at three stages of device completion.

The basic process with a single layer of mechanical polysilicon has been used to fabricate a myriad of devices. The obvious extension of the process is to multiple levels of mechanical polysilicon layers with intervening layers of sacrificial films. However, this extension is not without cost, and careful consideration of the advantages to be gained against the investment required to

Thus, the recent addition of chemical-mechanical polishing (CMP) planarization to Sandia's three-level technology eliminates the link/gear interference problem, as illustrated in Fig. 3. The benefits of CMP, best known for its global planarization use in sub-micron circuit technology[5], for surface micromachining are three-fold. In addition to eliminating the gear/link interference, an artifact of anisotropic etching of conformal polysilicon films over edges, often referred to as stringers, is also eliminated since there are no edges on a planar surface. Thirdly, the inclusion of additional levels of polysilicon becomes possible since the topology and associated photolithographic problems are also eliminated.

Examples of the types of micromechanical devices possible with this technology are now presented. Methods for monolithically integrating surface micromachining with CMOS circuitry are discussed in Section 5.

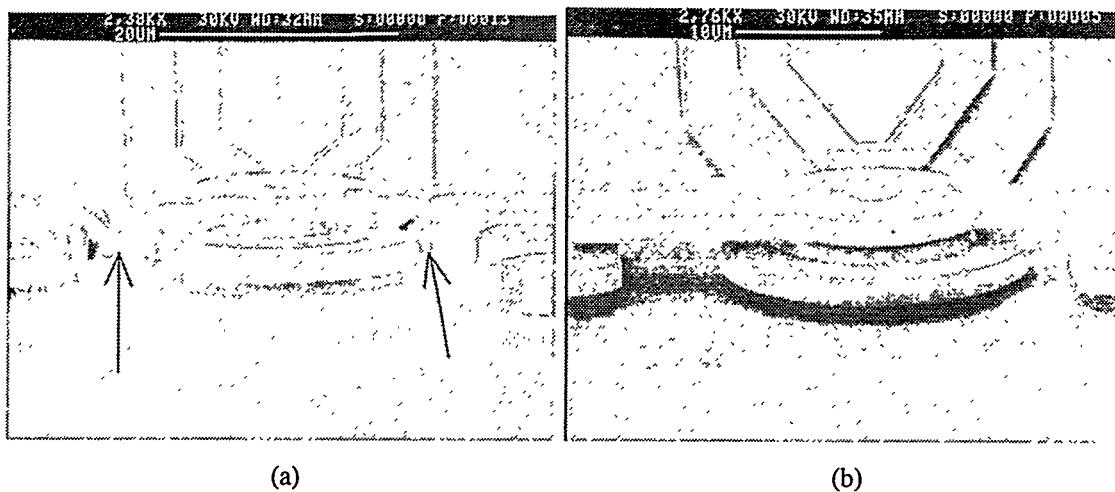


Fig. 3 The SEM Fig. 3a illustrates the artifacts generated by the conformal nature of the polysilicon depositions over prior topology (indicated by arrows), while Fig. 3b illustrates the same microengine joint feature fabricated with planarization by CMP before the final polysilicon deposition. The overhang artifacts are no longer present.

3. Sensors

The MDL has fabricated a number of sensors based on micromechanical technologies. The development of these sensors is driven by both industrial and defense applications.

Surface micromachined polysilicon filaments for use as catalytic gas sensors, flow sensors, and thermal-conductivity pressure gauges have been fabricated and characterized. These filaments are fabricated using a single-level doped polysilicon process. A sacrificial oxide is patterned to form both the anchor layer and a stiction-reducing dimple layer. Filaments over 1 mm in length have been fabricated without stress or sticking problems. A scanning electron micrograph (SEM) of a differential pair of filaments is shown in Fig. 4. One of these filaments is passivated with silicon nitride while the other is coated with a platinum catalyst. Fig. 5 is a close-up view of that catalytic coating and illustrates our ability to selectively coat these filaments. These filaments have been used to detect combustible gas mixtures. The response of the sensor to various concentrations of hydrogen in 20% oxygen is shown in Fig. 6. These filaments consume only milliwatts of power and can be operated in pulsed mode to reduce the average power consumption into the microwatt regime.

develop the process must be made. Earlier work by Fan, Tai and Muller [3] illustrated that mechanical elements such as fixed-axle pin joints, self-constraining pin joints, and constrained sliders can be made, and require, two layers of polysilicon. This work clearly indicated that the fabrication of movable, connected, mechanical elements are feasible with surface micromachining. However, complex, interactive mechanical devices require yet a third level of mechanical polysilicon to construct. This is easily seen by following Fig. 2a-c.

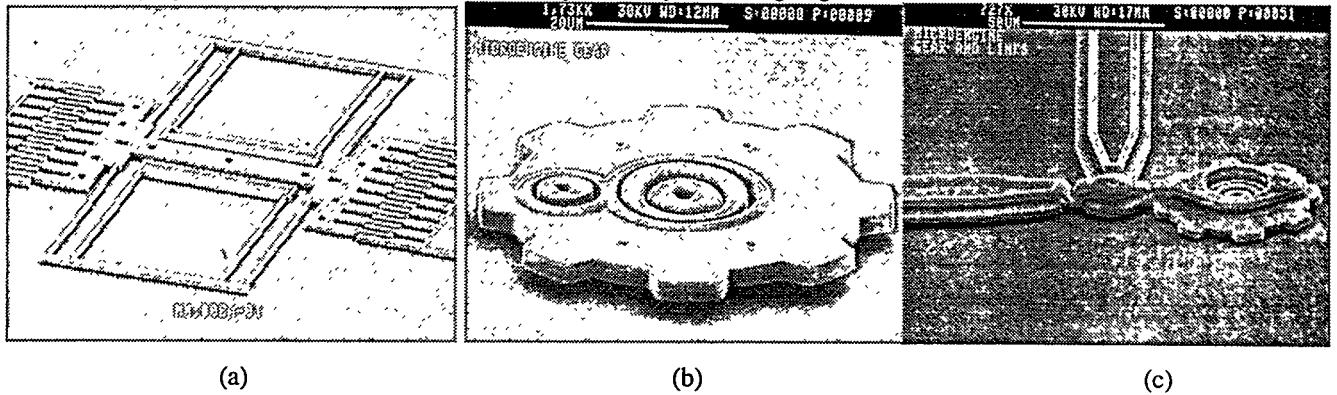


Fig. 2. a) Simple, yet very useful structures, particularly for sensor applications, can be fabricated using a single level of mechanical polysilicon. b) A double level process produces movable mechanical elements. However, connection to these structures is limited. Here a gear with a central hub attached to the substrate and a free-spinning pin along its radius is shown. However, connection to the radial pin is not possible without a third layer of polysilicon. c) A triple level process allows the fabrication of complex, interconnected, interactive mechanisms with actuators. That is, the gear in Fig. 2b is now connected to a linkage element and can be actuated upon by that element.

Although not clearly illustrated in Fig. 2, there is usually an additional polysilicon layer included in these processes. This polysilicon layer does not form mechanical elements, rather, it serves to form voltage reference planes and electrical interconnects. This film is not counted in the reference to single, double, and triple level processes.

Typically, structures constructed with one level of polysilicon have restricted movement through elastic members attached to the substrate. Although the degree of mechanical complexity possible with a single level process is limited, it can nevertheless produce very useful and commercially viable devices, particularly in sensor applications. One such example is Analog Device's surface-micromachined accelerometer [4], which is similar to the simple comb-drive pictured in Fig. 2a. Extension to a double-level process (Fig. 2b) begins to allow considerably greater mechanical design flexibility, particularly with regard to rotating elements. As seen in Fig. 2b, a free-spinning gear attached to the substrate with a free-spinning pin at some radius from its center can be produced. However, a third level of polysilicon is needed to couple energy to and from this gear. Fig. 2c illustrates this ability to interconnect elements with absolute, hard linkages for actuation purposes made possible through the use of three levels. Note also that any or all of the mechanical layers can be made electrically conductive, thus providing additional layers for electrical interconnect or electrodes. The full utility of the three-level process is best illustrated with the example of the Sandia microengine presented in Section 4.

The batch-fabrication of integrated gear-link assemblies by surface micromachining techniques presents a fundamental difficulty. Due to the vertical topology introduced by the deposition and etching of the various films used, this interference normally arises when the interconnecting link must pass over the gear edge, or the concentric retaining hub of the gear, as the mechanism moves through one complete rotational cycle. An example of this interference can be seen in Fig. 2c and close-up in Fig. 3a where the upper link runs over the edge of the gear causing an overhang feature. This feature is due to the conformal deposition of the polysilicon film. Link/gear interference can be alleviated by the microengine design, or by planarization of the surfaces before subsequent deposition of additional films.

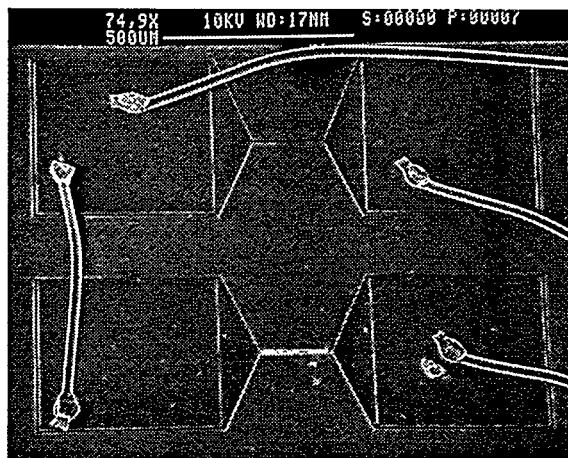


Fig. 4. Two polysilicon filaments for use as a combustible gas detector. The upper filament is passivated with silicon nitride. The lower filament has been selectively coated with a platinum catalyst.

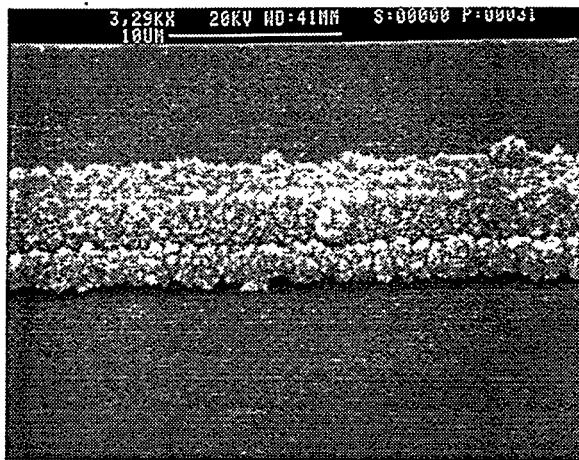


Fig. 5. A close-up view of the platinum-coated polysilicon filament.

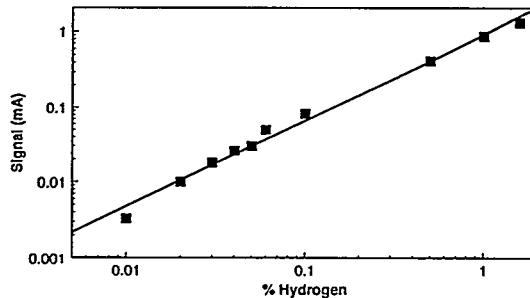


Fig. 6. The signal change from the detector pair shown in Fig. 4 to various concentrations of hydrogen in a 20% oxygen ambient.

A pressure sensor technology [6] similar to that of Burns [7] has been developed at the MDL based upon a silicon nitride layer as the diaphragm material. A sacrificial oxide underneath this diaphragm layer is etched away using HF-based chemistries. This leaves a cavity beneath the diaphragm. An additional silicon nitride layer is used to seal the cavity in near-vacuum conditions (approx. 200 mTorr). Polysilicon piezoresistors are deposited on the diaphragm to sense the diaphragm strain that results from changes in ambient pressure. A completed, 100 micron

diameter pressure sensor is shown in Fig. 7. The response of that sensor to pressure changes is shown in Fig. 8.

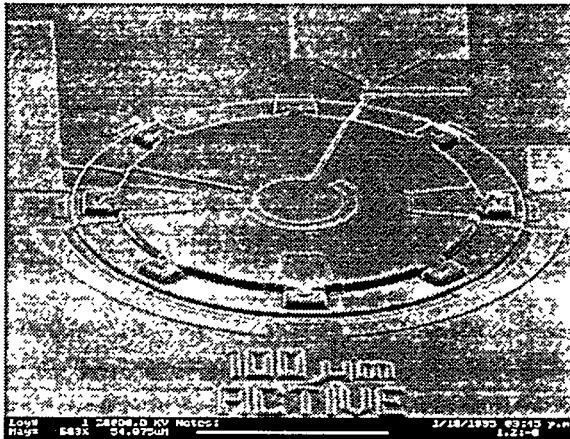


Fig. 7. An SEM of a surface micromachined pressure sensor. The pressure sensor uses polysilicon piezoresistors on a nitride diaphragm over a vacuum cavity to sense changes in ambient air pressure.

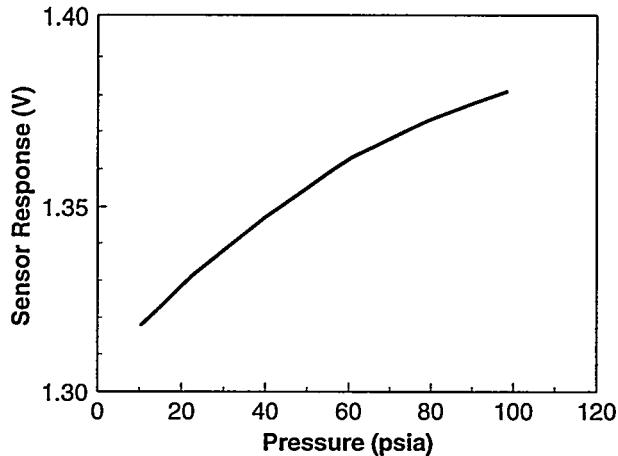


Fig. 8. The response of a surface-micromachined pressure sensor with a 100 micron diameter diaphragm to changes in applied pressure.

Micromachined force-feedback accelerometers and gyroscopes are also being investigated. Approaches to improve the sensitivity of such structures by increasing the mass of the structures are being pursued. Additionally, force-feedback sensors are being used as a technology development vehicle for monolithically integrating micromechanical structures with CMOS in a batch fabricated process. This integration will be discussed later in section 5.

In addition to these micromechanical sensing technologies, the MDL also has developed a robust, wide-range hydrogen sensor [8] with integrated control and interface electronics. This chip shown in Fig. 9 illustrates the capability at the MDL to integrate sensing technologies with controlling CMOS. The controlling electronics include analog control elements, A/D converters, D/A converters, and a network communication interface. The sensor utilizes a Pd/Ni alloy in both a chemi-resistor and a chemFET to sense hydrogen concentration from the ppm level to pure hydrogen. The chip also contains heaters, a thermometer, and the necessary control electronics which enable the chip to maintain a constant temperature under changing environmental

conditions. Fig. 10 shows the response of the chemi-resistor and chemFET on the hydrogen sensor.

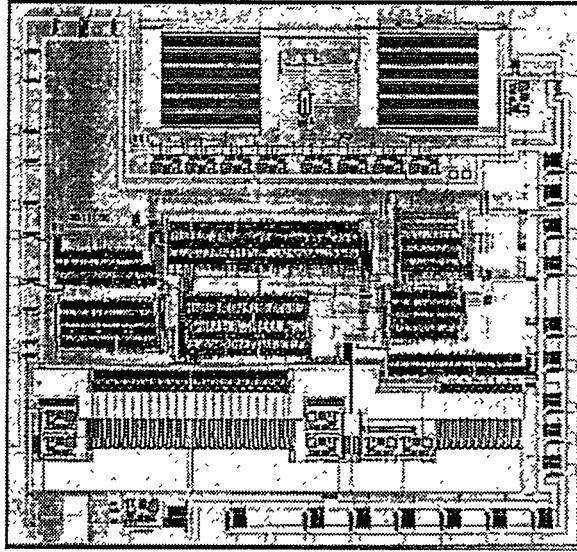


Fig. 9. A robust, wide-range hydrogen sensor complete with integrated control and interface electronics.

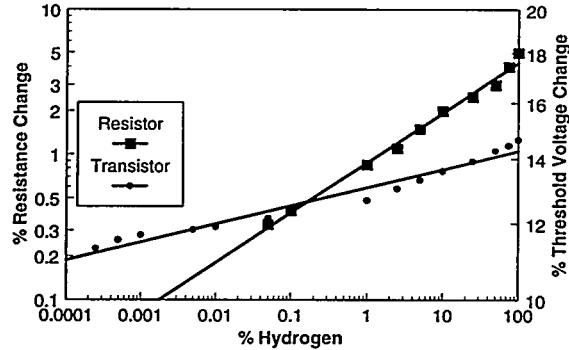


Fig. 10. The response of both the resistor and transistor on the hydrogen sensor to various concentrations of hydrogen.

Although, strictly speaking, not a micromachined device, the hydrogen sensor illustrates the utility of the integration of circuitry with a basic sensor element and demonstrates the feasibility of combining two dissimilar technologies.

4. Actuators

Micromechanical actuators have not seen the wide-spread industrial use that micromechanical sensors have achieved. Two principal stumbling blocks to their widespread application have been low force/torque levels and difficulty in coupling tools to engines. The MDL has two development projects that are overcoming these issues. A steam-based actuation mechanism [9] generates orders of magnitude higher force per unit chip area than conventional electrostatic actuators. Also, with the three-level polysilicon micromachining process, the ability to couple tools to microengines and produce useful work is now present.

The steam engine, shown in Fig. 11, employs a polysilicon piston that moves inside a polysilicon cylinder. The seal between the piston and cylinder is provided by the meniscus formed during the operation of the device. A small amount of water is pulled into the boiler through capillary action. It is then heated with a polysilicon heater inside the boiler, causing the formation

of a bubble which pushes the piston out of the cylinder. Springs provide a return force for the piston when the heat is removed and the bubble collapses.

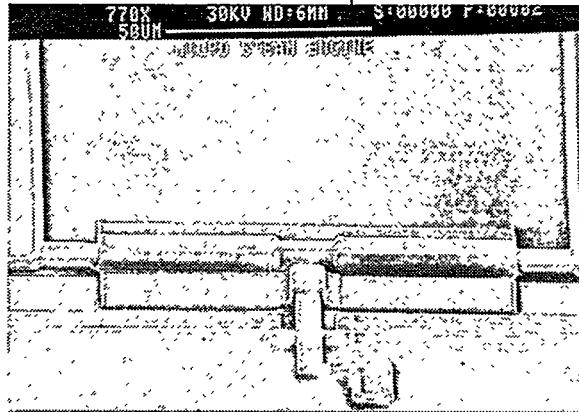


Fig. 11. The micro steam engine. The piston, seen entering the cylinder at the bottom center, is suspended by two folded beams attached to the substrate. Piston dimensions are 2 microns thickness, 6 microns width, with measurable displacement designed to be 10 microns.

More intricate actuation mechanisms require advanced mechanical designs coupled with additional levels of structural materials. Fig. 3 illustrates a pin joint linkage formed between two layers of mechanical poly. This pin joint is one of the linkage elements used in coupling the electrostatic microengine to other micromechanisms. The three-level process is fully utilized by the microengine shown in Fig. 12. Here, two linear electrostatic comb-drive actuators drive a set of linkages to a rotary gear [2]. This gear can be rotated by applying sinusoidal driving forces 90° out of phase with each other to each of the comb-drive actuators. This is analogous to the operation of two orthogonal pistons connected to a crankshaft. Operation of the small gears at rotational speeds in excess of 200,000 revolutions per minute has been demonstrated. This smaller gear can then be used to drive other gears or gear trains [10]. The operational lifetime of these devices exceed 8×10^8 revolutions.

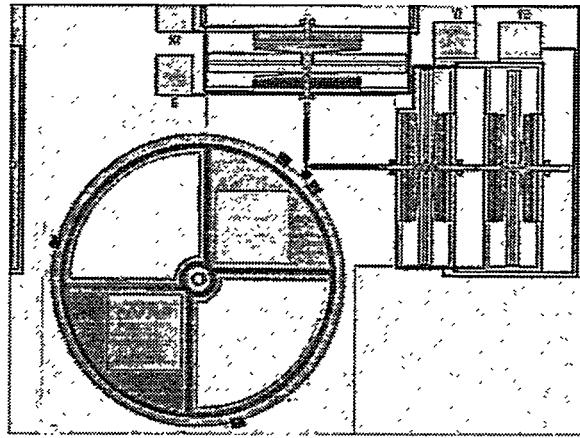


Fig. 12. Two sets of linear comb-drive actuators are linked to a 50 micrometer diameter drive gear. This smaller gear drives a 1.6 mm diameter shutter in the lower left of the photo.

5. CMOS/Micromechanics Integration

Finally, the task of integrating micromechanics with CMOS is being undertaken. The MDL has successfully integrated CMOS with the chemFET sensing technology of the hydrogen sensor, but the issues involved in integrating CMOS with micromechanics are much more involved due to the intricacy of the micromechanical processing. Micromechanical structures typically require long, high-temperature anneals to assure that the stress in the structural materials of the micromechanical structures has completely relaxed, although work by researchers at Berkeley is continuing to lower the required thermal budget for stress reduction in polysilicon [11]. On the other hand, CMOS technology requires planarity of the substrate to achieve high resolution in the photolithographic process. If the micromechanical processing is performed first, the substrate planarity is sacrificed. If the CMOS is built first, it (and its metallization) must withstand the high-temperature anneals of the micromechanical processing. This second alternative was chosen by researchers at Berkeley [12] and is being developed further at the MDL. In this approach, the standard aluminum metal used in CMOS is replaced with tungsten. Since tungsten is a refractory metal, it withstands the high-temperature processing, but a number of issues remain unsolved concerning the adhesion of the tungsten layer and the unwanted formation of tungsten silicides. Despite these issues, the MDL has fabricated integrated devices with functioning control electronics. One such device, an accelerometer with on-chip amplifiers, is shown in Fig. 13.

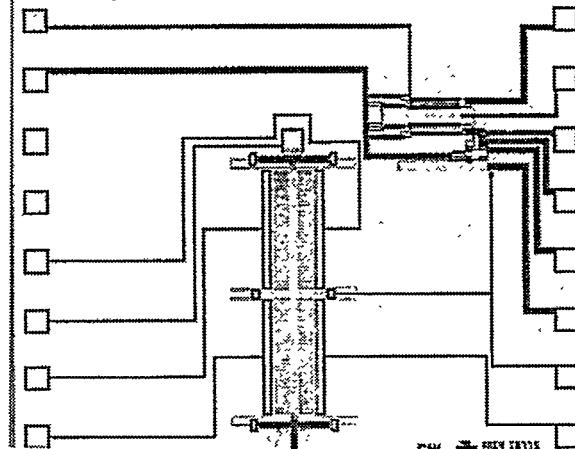


Fig. 13. A micromachined accelerometer integrated with an all-tungsten CMOS pre-amp.

Alternatively, a unique micromechanics-first approach [13] is also being developed at Sandia. In this approach, micromechanical devices are fabricated in a trench etched on the surface of the wafer. After these devices are complete, the trench is refilled with oxide, planarized using CMP, and sealed with a nitride membrane. The wafer with the embedded micromechanical devices is then processed using conventional CMOS processing with aluminum metallization. Additional steps are added at the end of the CMOS process in order to expose and release the embedded micromechanical devices. A cross-section of this technology is shown in Fig. 14.

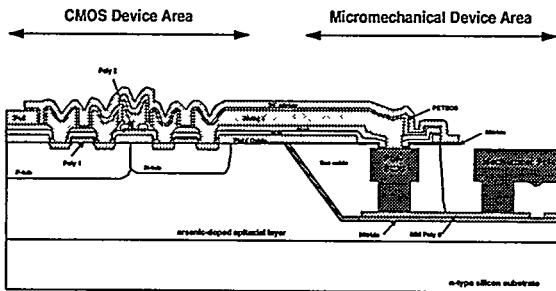


Fig. 14. A schematic cross-section of the embedded micromechanics approach to CMOS/MEMS integration.

Integration is not necessarily the answer for every micromechanical device application. However, the primary goal of integration is to enhance the functionality of micromechanical devices. For example, this can be accomplished by integration of control and communication electronics with sensors and actuators to reduce overall size and provide 'smart' processing and communication. Also, increased sensitivity can be accomplished for certain classes of sensor mechanisms by providing near-by signal-processing electronics. For large volume production, the per unit function cost may be reduced.

6. Summary

Polysilicon surface micromachining is a process technology that Sandia has exploited for a variety of micromechanical sensors and actuators. The general process available provides three-levels of polysilicon for mechanical constructions such as simple doubly-clamped beams for sensing to intricate interconnected linkages and joints for actuation. The basic process has been enhanced by the inclusion of CMP to allow easier mechanical design and processing while offering the extension to additional levels of polysilicon. Finally, two technology approaches leading to the monolithic integration of CMOS microelectronics with surface micromechanics promise to offer system integration, greater sensitivity, smart sensing and actuation, and possibly lower cost.

7. Acknowledgments

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