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Micromachined Sensor and Actuator Research at Sandia's Microelectronics Development Laboratory

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ABSTRACT

An overview of the major sensor and actuator projects using the micromachining capabilities of the Microelectronics Development Laboratory at Sandia National Laboratories are presented. Development efforts are underway for a variety of micromechanical devices and control electronics for those devices.

Our efforts are concentrated in the area of surface micromachining. Pressure sensors based on silicon nitride diaphragms and hot polysilicon filaments for calorimetric gas sensing have been developed. Accelerometers based upon high-aspect ratio surface micromachining are being developed. Actuation mechanisms employing either electrostatic or steam power are being combined with a three-level active (plus an additional passive level) polysilicon surface micromachining process to couple these actuators to external devices.

The results of efforts toward integration of micromechanics with the driving electronics for actuators or the amplification/signal processing electronics for sensors is also described. This effort includes a CMOS-first, tungsten metallization process to allow the CMOS electronics to withstand high-temperature micromechanical processing. Also, a unique micromechanics-first approach is being pursued in which the micromechanical devices are embedded below the surface of the starting material for the CMOS.

1. FACILITIES

The Microelectronics Development Laboratory (MDL), shown in Figure 1, 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 laboratory's efforts in micromechanics and how they relate to the laboratory's other development efforts in smart sensors 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 other technologies benefit from the wide variety of equipment and processes in existence to support the baseline CMOS, but these other technologies must also maintain a degree of compatibility with CMOS manufacturing processes so that they do not contaminate those processes.

In the area of micromechanics, the MDL has development projects in both surface and bulk micromachining. Because bulk micromachining raises a number of contamination issues and does not take full advantage of the capabilities of the facility, the majority of the work underway at the MDL is being performed in the surface-micromachining area. 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 both blanket and selective CVD processes.

2. SENSORS

The MDL has fabricared 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 level. 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 Figure 2. One of these filaments is passivated with silicon nitride while the other is coated with a platinum catalyst. Figure 3 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

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various concentrations of hydrogen in 20% oxygen is shown in Figure 4. These filaments consume only milliwatts of power and can be operated in pulsed mode to reduce the average power consumption to the microwatts.

A pressure sensor technology[1] 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 Figure 5. The response of that sensor to pressure changes is shown in Figure 6.

Micromachined force-feedback accelerometers and gyroscopes are also being investigated. Approaches to improve the sensitivity of such structures by increasing both the aspect ratio and mass of the structures while decreasing parasitics 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 this paper.

Bulk micromachining of single crystal quartz was used to produce the volatile organic sensor shown in Figure 7. This sensor has been described in more detail elsewhere[2]. This sensor uses three bulk acoustic wave resonators to sense mass changes in films deposited on those resonators. The quartz resonant elements are 1.2 mm in diameter and approximately 75 microns thick. They have a resonant frequency of 22 MHz. Figure 8 illustrates the time-dependent response of one of these resonators coated with 0.1 microns of poly-isobutylene to varying concentrations of trichloroethylene. The magnitude of the frequency shifts for this coated sensor to five different organic solvents and water is shown in Figure 9. Additionally, a custom driver chip[3] attached to the quartz contains circuitry for temperature compensation, frequency counting, and signal multiplexing.

In addition to these micromechanical sensing technologies, the MDL also has developed a robust, wide-range hydrogen sensor[4] with integrated control and interface electronics. This chip shown in Figure 10 illustrates the ability of 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. Figure 11 shows the response of the chemi-resistor and chemFET on the hydrogen sensor.

3. ACTUATORS

Micromechanical actuators have not seen the widespread industrial use that micromechanical sensors have achieved. Two principal stumbling blocks to their widespread application have been low torque and difficulty in coupling tools to engines. The MDL has two development projects that are overcoming these issues. A steam-based actuation mechanism[5] generates orders of magnitude higher force per unit chip area than conventional electrostatic actuators. Also, a new three-level polysilicon micromachining process greatly enhances one's ability to couple tools to microengines.

The steam engine, shown in Figure 12, employs a polysilicon piston that moves inside a polysilicon cylinder. The seal between the piston and cylinder is provided by the meniscus force of a drop of water covering 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.

More intricate actuation mechanisms require advanced mechanical designs coupled with additional levels of structural materials. A new micromachining process described elsewhere in detail[6] includes three movable levels of polysilicon in addition to a stationary level for a total of four levels of polysilicon. These levels are each separated by sacrificial oxide layers. An additional friction-reduction layer of silicon nitride is placed between the layers that form bearing surfaces. Figure 13 illustrates a bearing formed between two layers of mechanical poly. A total of 8 mask levels are used in this process. This process has first been applied to the microengine shown in Figure 14. Here, two comb-drive actuators[7] drive a set of linkages to a rotary gear. This gear can be rotated by applying sinusoidal driving forces 90° out of phase with each other to each of the comb-drive actuators. Operation of the small gears at rotational speeds in excess of 200,000 revolutions per minute has been demonstrated. The operational lifetime of these devices exceed 8×10^{8} revolutions. This smaller gear can then be used to drive other gears or gear trains.[8]

4. CMOS/MICROMECHANICS INTEGRATION

Finally, the task of integrating micromechanics with the controlling 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 require long, high-temperature anneals to assure that the stress in the structural materials of the micromechanical structures has completely relaxed. 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[9] 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 with 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 Figure 15.

A unique micromechanics-first approach[10] 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 chemical-mechanical polishing, and sealed with a nitride membrane. The wafer with the embedded micromechanical devices is then processed using conventional CMOS processing. 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 Figure 16.

5. SUMMARY

Sandia's Microelectronics Development Laboratory has developed and is advancing a broad range of sensors and actuators using micromechanical processing techniques. Combustible gas detectors, flow sensors, and vacuum gauges based on hot polysilicon filaments have been produced. Accelerometers and gyroscopes with integrated feedback and amplifying circuitry are also being developed. A micromachined steam engine, a volatile organic sensor technology, and a pressure sensing technology have been developed. A new three-level polysilicon process enables intricate coupling mechanisms that link linear comb-drive actuators to multiple rotating gears. Two technologies leading to the monolithic integration of micromechanical and microelectronic are being developed.

6. ACKNOWLEDGEMENTS

This paper outlines the work of a number of people at the Microelectronics Development Laboratory including C. Barron (Accelerometers), P. McWhorter (Integrated Micromechanics, Microsensors, & CMOS Technology Department Manager), S. Montague (CMOS/MEMS Integration), A. Ricco (Gas Sensors), J. Rodriguez (Hydrogen Sensor), J. Sniegowski (Actuators), and H. Weaver (Microelectronics Development Laboratory Manager). The process development engineers, operators, and technicians of the Microelectronics Development Laboratory should also be acknowledged for their contributions to the process development, fabrication, and testing of these devices.

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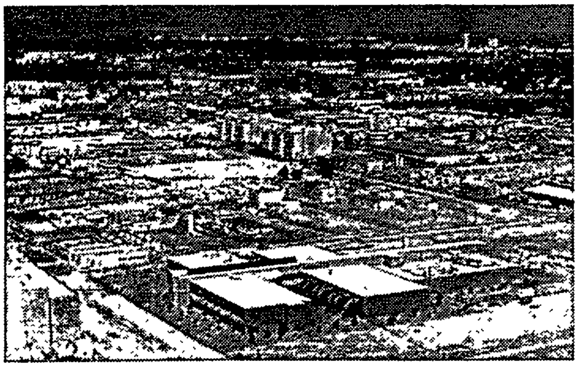

Figure 1. The Microelectronics Development Laboratory at Sandia National Laboratories in Albuquerque, NM.

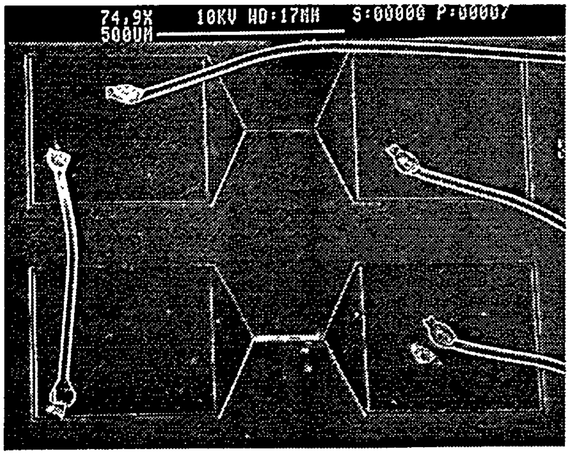

Figure 2. Two polysilicon filaments for use as a combustible gas detector. The upper filament is passivated with silicon nitride. The lower filament has been selectively coated with a platinum catalyst.

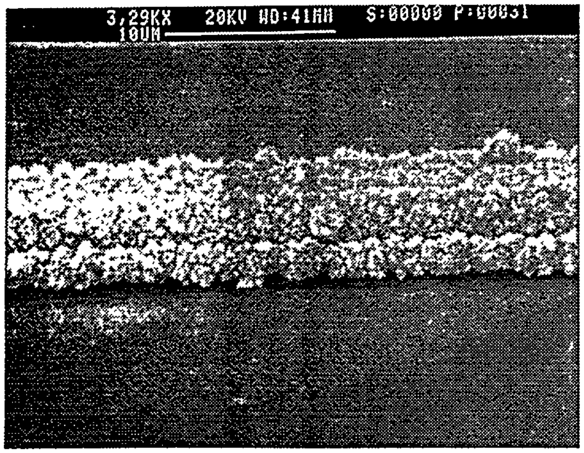

Figure 3. A close-up view of the platinum-coated polysilicon filament.

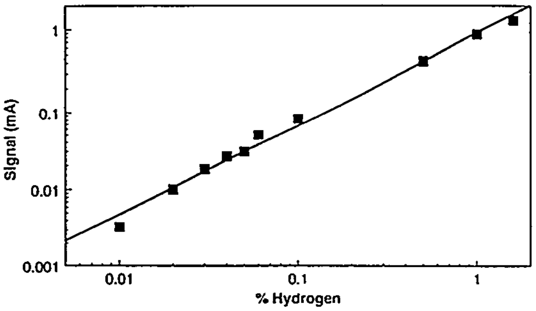

Figure 4. The signal change from the detector pair shown in Figure 2 to various concentrations of hydrogen in a 20% oxygen ambient.

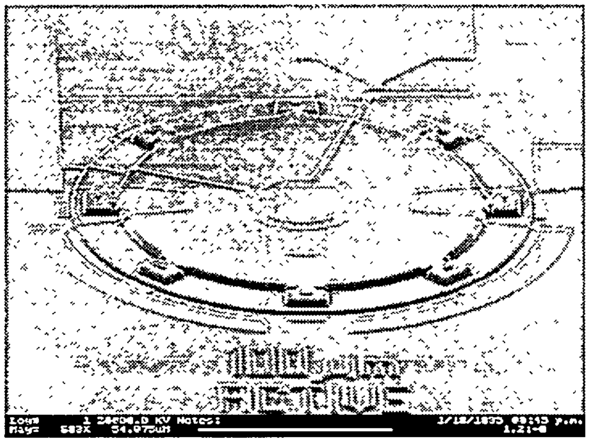

Figure 5. An SEM of a surface micromachined pressure sensor. The pressure sensor uses polysilicon piezoresistors on a nitride diaphragm over a vacuum cavity to sense changes in ambient air pressure.

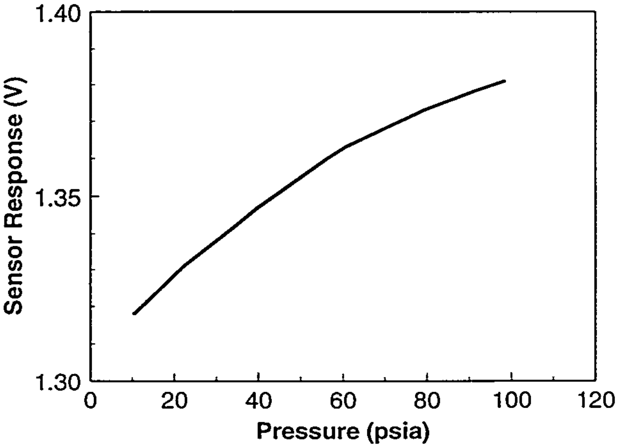

Figure 6. The response of a surface-micromachined pressure sensor with a 100 micron diameter diaphragm to changes in applied pressure.

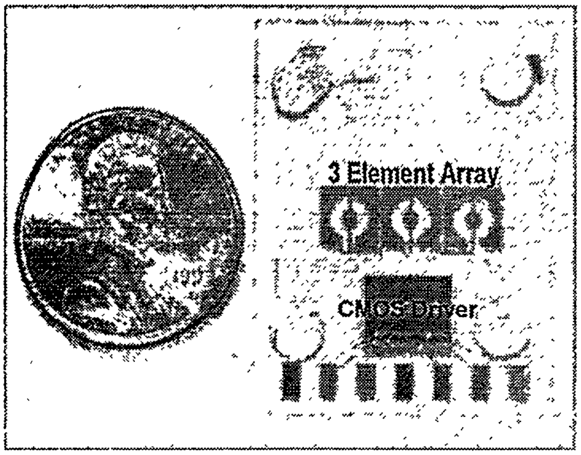

Figure 7. A three element volatile organic sensor with integrated driving, temperature compensation, and multiplexing electronics.

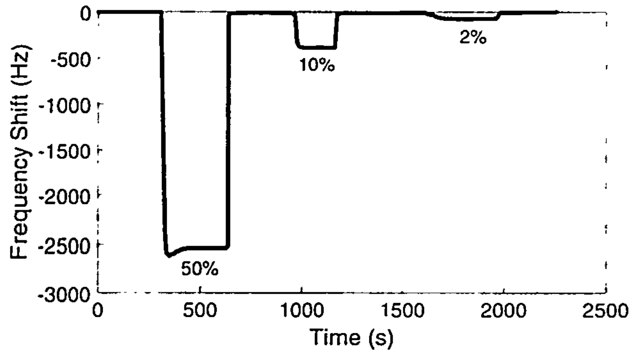

Figure 8. The time-dependent response of the quartz sensor platform coated with 0.1 microns of poly-isobutylene to various concentrations (50%, 10% and 2% of saturation vapor pressure) of trichloroethylene in nitrogen at 20°C.

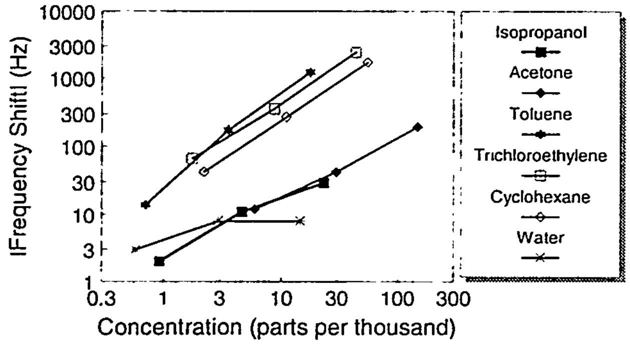

Figure 9. The magnitude of the response of the quartz sensor platform coated with 0.1 microns of poly-isobutylene to various concentrations of 5 organic solvents and water.

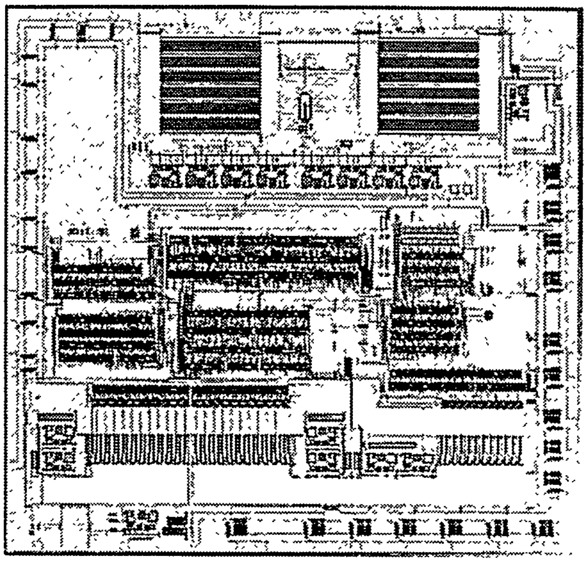

Figure 10. A robust, wide-range hydrogen sensor complete with integrated control and interface electronics.

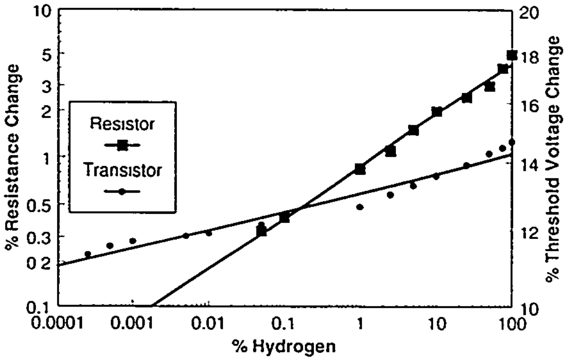

Figure 11. The response of both the resistor and transistor on the hydrogen sensor to various concentrations of hydrogen.

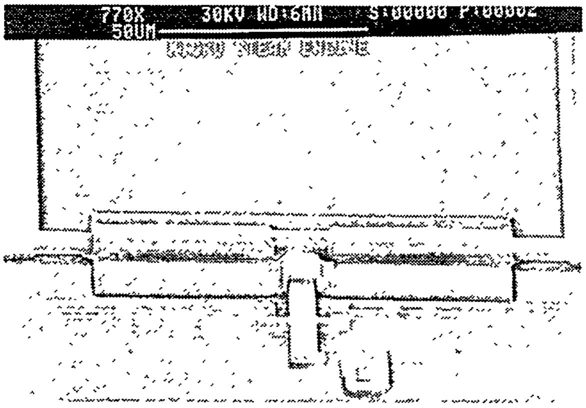

Figure 12. The micro steam engine.

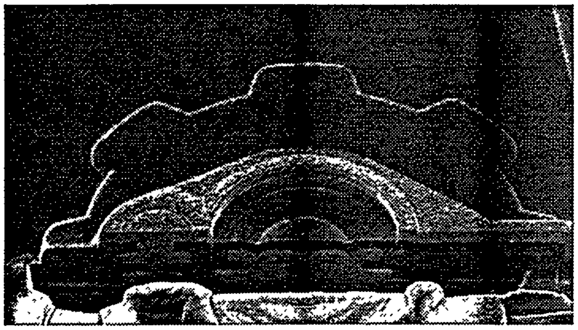

Figure 13. A focused ion-beam cross-sectional image of a gear produced with the MDL's three level polysilicon process.

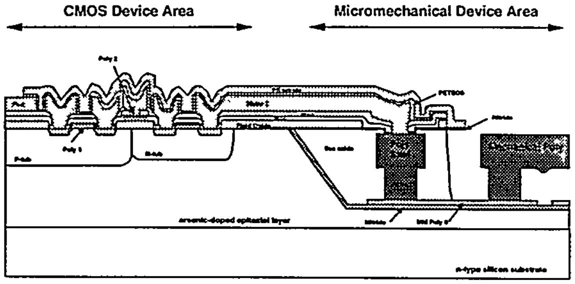

Figure 16. A schematic cross-section of the embedded micromechanics approach to CMOS/MEMS integration.

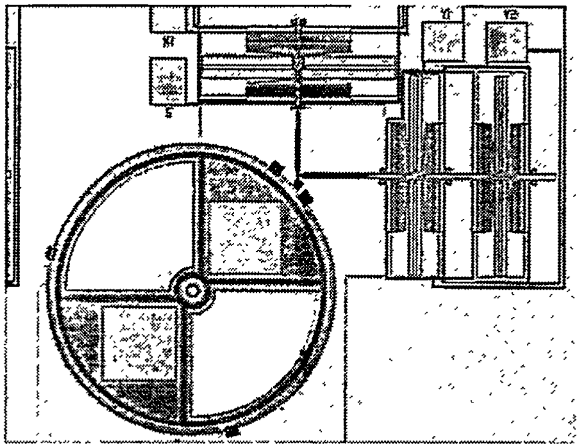

Figure 14. Two sets of linear comb-drive actuators driving the gear shown in Figure 13. This smaller gear drives a 1.6 mm diameter shutter in the lower left of the photo.

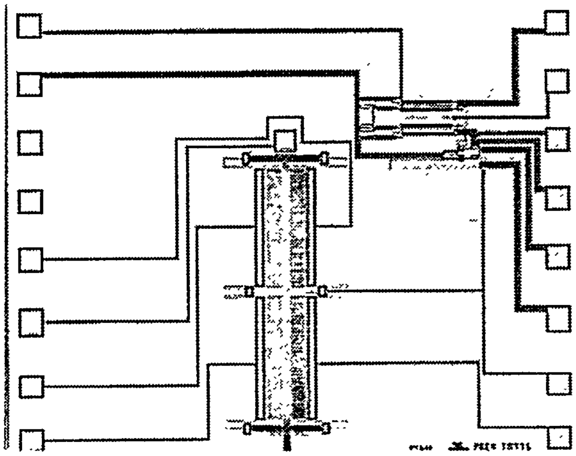

Figure 15. A micromachined accelerometer integrated with an all-tungsten CMOS pre-amp.