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MICROMACHINED SENSOR AND ACTUATOR RESEARCH AT SANDIA'S MICROELECTRONICS DEVELOPMENT LABORATORY

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Abstract

An overview of surface micromachining projects at the Microelectronics Development Laboratory of Sandia National Laboratories is presented. Development efforts are underway for a variety of surface micromachined sensors and actuators. A technology that embeds micromechanical devices below the surface of the wafer prior to microelectronics fabrication has also been developed for integrating microelectronics with surface micromachined micromechanical devices.

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. 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, such as micromechanics, 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 they 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, although surface micromachining constitutes the majority of the MDL's efforts and is emphasized here.

Sensors

The MDL has fabricated a number of sensors based on micromachining technologies. Surface micromachined polysilicon filaments similar to those developed by researchers at U.C. Berkeley[1] for use as catalytic gas sensors, flow sensors, and thermal-conductivity pressure gauges have been 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. 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. These filaments have been used to detect combustible gas mixtures and can clearly detect levels as low as 100 ppm of H_2 in air as shown by the sensor response in Figure 3. The filament pairs consume milliwatts of power when operated in a continuous mode and can be operated in pulsed mode to reduce the average power consumption to microwatts.

A planar pressure sensor technology similar to a non-planar technology developed at U. of Wisconsin[2] has been developed at the MDL[3] based upon a silicon nitride layer as the diaphragm material. A trench is etched ~2 microns deep in the surface of a silicon wafer. This trench is refilled with a sacrificial oxide and planarized with chemical-mechanical polishing. A silicon nitride diaphragm layer is then deposited. The sacrificial oxide underneath this diaphragm layer is etched using HF leaving 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 4. The sensor's response is illustrated in Figure 5.

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 torque and difficulty in coupling tools to engines. The MDL has development projects that are overcoming these issues. A steam-based actuation mechanism[4], shown in Figure 6, generates orders of magnitude higher force per unit chip area than conventional electrostatic actuators. Also, our three-level polysilicon micromachining process[5] enables the fabrication of devices with increased degrees of complexity that greatly enhance the ability to couple tools to engines.

This three-level process 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. A total of eight mask levels are used in this process. An additional friction-reduction layer of silicon nitride is placed between the layers that form bearing surfaces. The inset (lower right) to Figure 7 illustrates a bearing formed between two layers of mechanical poly. The overall photo in Figure 7 shows two comb-drive actuators[6] driving a set of linkages to a set of rotary gears. This engine 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 (shown in the inset) at rotational speeds in excess of 300,000 revolutions per minute has been demonstrated. The operational lifetime of these small devices exceed 8×10^8 revolutions. This smaller gear is shown driving a larger (1.6 mm diameter) gear[7] in Figure 7. This larger gear has been driven as fast as 4800 rpm.

CMOS/Micromechanics Integration

Finally, the task of integrating micromechanics with the controlling CMOS is being undertaken. As recently summarized in a review paper by Howe[8], 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 U. C. Berkeley[9] and has been examined 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. However, 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, although both device yield and performance were less than optimal.

A unique micromechanics-first approach[10] has also been 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. Completed devices are shown in Figure 8. A cross-section of this technology is shown in Figure 9.

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 based on hot polysilicon filaments and pressure sensors based on sealed nitride diaphragms have been produced. A three-level polysilicon process enables intricate coupling mechanisms that link linear comb-drive actuators to multiple rotating gears. A new technology where micromachined devices are embedded below the surface of a wafer prior to fabrication of microelectronic devices has also been developed.

Acknowledgments

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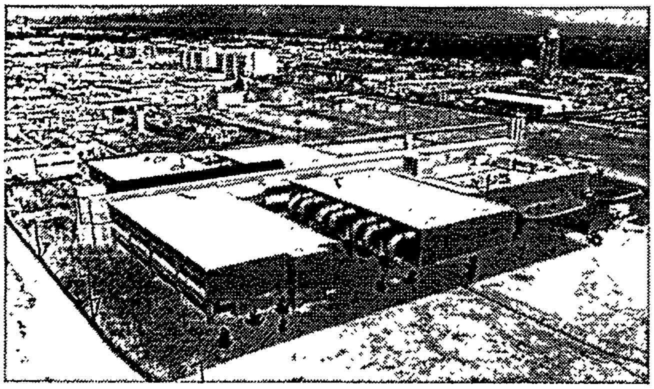

Figure 1. The Microelectronics Development Laboratory at Sandia National Laboratories in Albuquerque, NM.

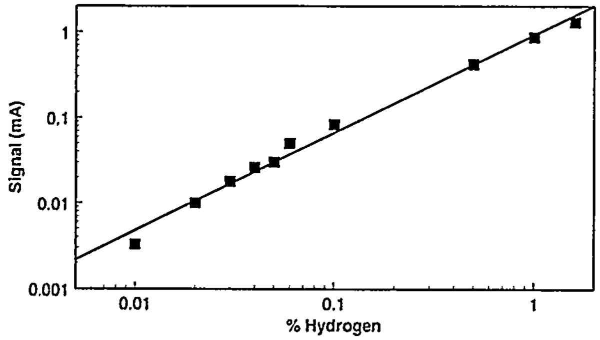

Figure 3. The signal change from the detector pair shown in Figure 2 to various concentrations of hydrogen in a 20% oxygen ambient.

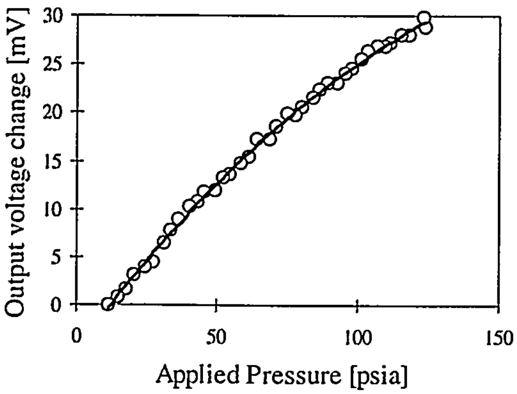

Figure 5. Output voltage vs. applied pressure for a 100 μm diameter pressure sensor.

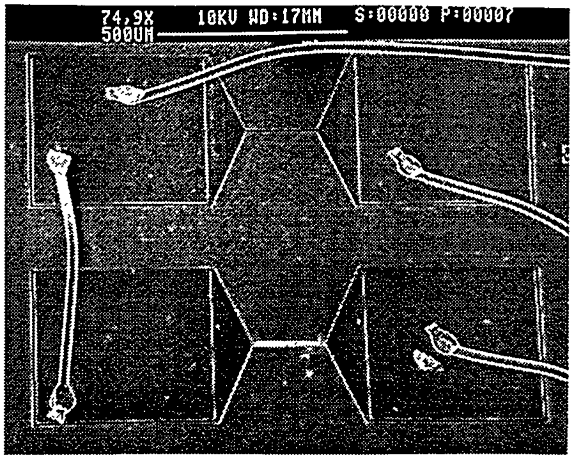

Figure 2. Two polysilicon filaments for use as a combustible gas detector. The upper filament is passivated with silicon nitride. The lower filament has been selectively coated with a platinum catalyst.

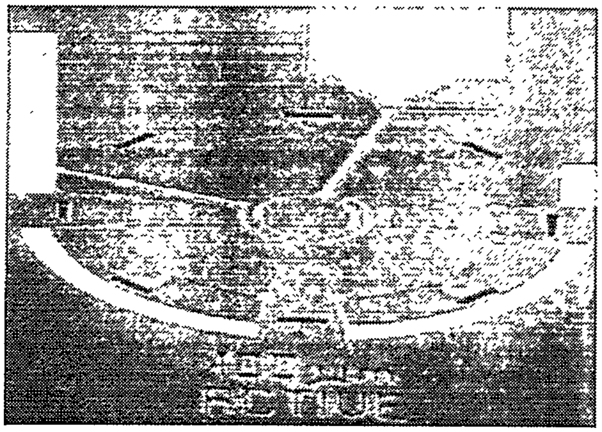

Figure 4. An SEM of a planar, surface-micromachined pressure sensor. The pressure sensor uses polysilicon piezoresistors on a nitride diaphragm over a vacuum cavity to sense changes in ambient air pressure.

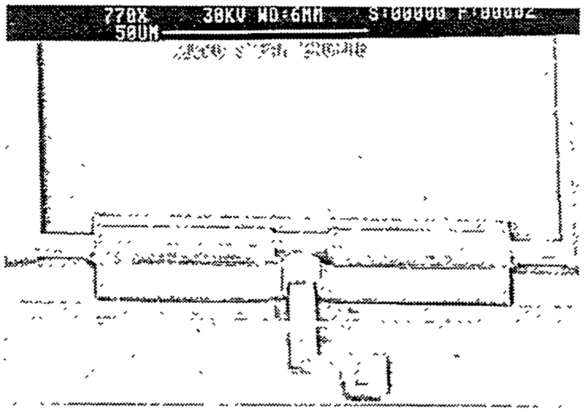

Figure 6. The micro steam engine.

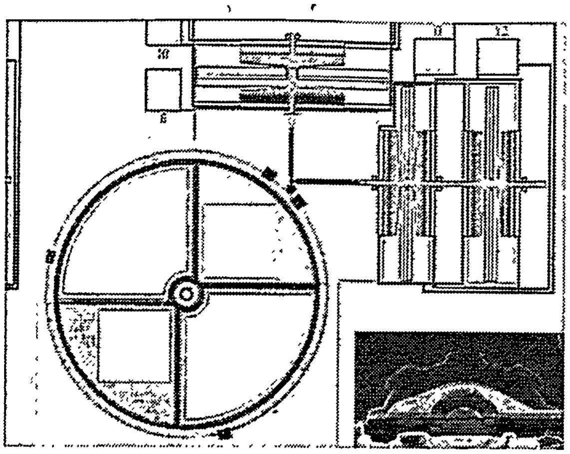

Figure 7. Two sets of linear comb-drive actuators driving the gear shown in the inset. This smaller gear drives a 1.6 mm diameter shutter in the lower left of the photo. Inset (lower right) shows a focused ion-beam cross-sectional image of the small gear.

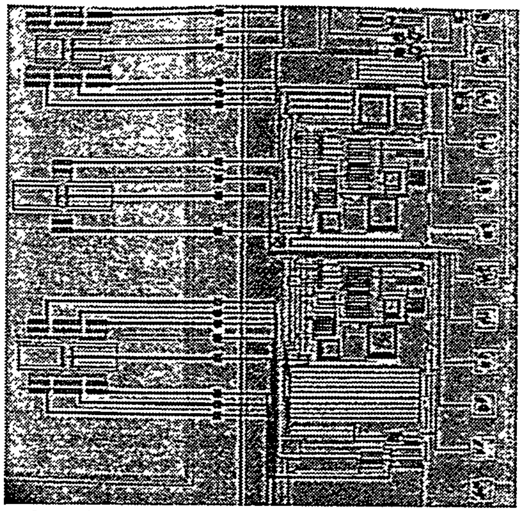

Figure 8. Micromachined resonators (left) next to their CMOS driving electronics (right) fabricated using the embedded micromechanics integration process.

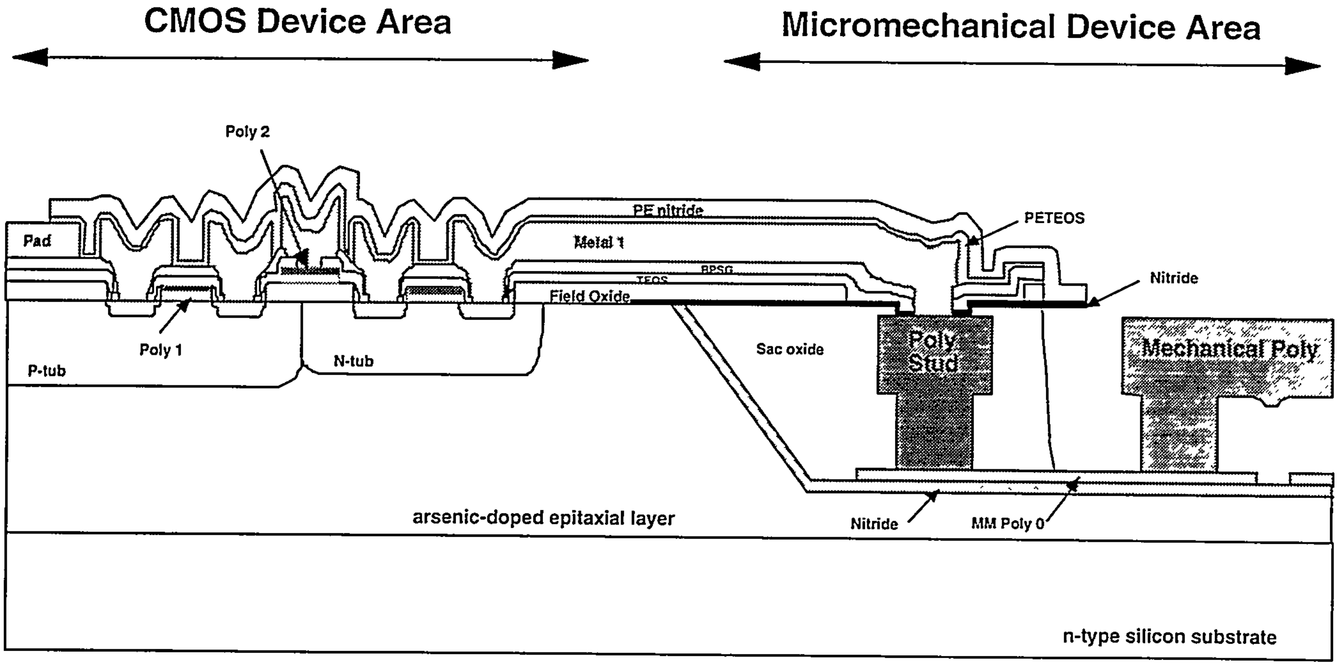

Figure 9. A schematic cross-section of the embedded micromechanics approach to CMOS/MEMS integration.

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