Micromachined Systems-on-a-Chip: Technology and Applications

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Abstract
Sacrificial polysilicon surface micromachining is emerging as a technology that enables the mass production of complex microelectromechanical systems by themselves or integrated with microelectronic systems. Early versions of these micromachined systems-on-a-chip have already found application in the commercial world as acceleration sensors for airbag deployment (for example, ADI’s ADXLS0). Two technologies described here, enable systems with increasing degrees of complexity to be fabricated. The first is a three-level polysilicon micromachining process which includes a fourth polysilicon electrical interconnect level, while the other is a single-level (+ second electrical interconnect level) polysilicon surface micromachining process integrated with 1.25 micron CMOS. Samples of systems-on-a-chip built in these processes such as combination locks, pop-up mirrors, and multi-axis accelerometers are also given.

Integrated Microelectronic/Micromechanical Systems-on-a-Chip

Recently, a great deal of interest has developed in manufacturing processes that allow the monolithic integration of MicroElectroMechanical Structures (MEMS) with driving, controlling, and signal processing electronics. This integration promises to improve the performance of micromechanical devices as well as reduce the cost of manufacturing, packaging, and instrumenting these devices by combining the micromechanical devices with an electronic sub-system in the same manufacturing and packaging process. For example, Analog Devices has developed and marketed an accelerometer¹ which demonstrates the viability and commercial potential of integration. They accomplished this task by interleaving, combining, and customizing their manufacturing processes which produce the micromechanical devices with the processes that produce the electronics. In another approach, researchers at Berkeley² have developed a modular integrated approach in which the aluminum metallization of CMOS is replaced with tungsten to enable the CMOS to withstand subsequent micromechanical processing.

As recently summarized in a review paper by Howe³, micromechanical structures require long, high-temperature anneals to ensure 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.

Figure 1. Micromachined resonators (left) next to their CMOS driving electronics (right) fabricated using the embedded micromechanics integration process.

A unique micromechanics-first approach⁴ which overcomes the planarity issues of building the MEMS before the CMOS has 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...
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at the end of the CMOS process in order to expose and release the embedded micromechanical devices. Completed devices are shown in Figure 1. A cross-section of this technology is shown in Figure 2. This technology has also been named as one of the recipients of the 1996 R&D 100 Award.

A collaboration with designers from the Berkeley Sensor and Actuator Center (BSAC) has recently started. BSAC designs for inertial measurement units (three-axis acceleration and three-axis rotation rate) have been built using Sandia's Modular, Monolithic Micro-Electro-Mechanical Systems (M*MEMS) technology. Initial lots of devices have been fabricated and the results from accelerometers built in this technology are reported in the next section.

The performance of the device is summarized in Table 1 below. Approximately an order of magnitude increase in sensitivity is seen over the commercial devices described previously. The accelerometer chip also includes clock generation circuitry, a digital output, and photolithographic alignment of the sense axes. Thus, this system-on-a-chip is a realization of a full three-axis inertial measurement unit that does not require manual assembly and alignment of sense axes.

Although the bias stability of this accelerometer system has yet to be assessed, these noise numbers indicate that this system can now begin to find application in military systems such as
- stability control
- attitude heading reference
- short time of flight navigation
and commercial applications such as
- automotive control
- automotive diagnostics
- automotive navigation
- virtual reality environmental sensing.
Table 1. Performance of the three-axis accelerometer as reported by Lemkin, et al.5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>X-axis</th>
<th>Y-axis</th>
<th>Z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Floor (µg/√Hz)</td>
<td>110</td>
<td>160</td>
<td>990</td>
</tr>
<tr>
<td>Dynamic Range (dB, 100 Hz Bandwidth)</td>
<td>84</td>
<td>81</td>
<td>70</td>
</tr>
<tr>
<td>Proof Mass (µgram)</td>
<td>0.38</td>
<td>0.26</td>
<td>0.39</td>
</tr>
<tr>
<td>Resonant Frequency (kHz)</td>
<td>3.2</td>
<td>4.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Power Dissipation (mW)</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Sampling Rate (kHz)</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

A combined X/Y-axis rate gyro and a Z-axis rate gyro have also been designed by researchers at U.C. Berkeley and are presently being fabricated in this new manufacturing process to yield a full six-axis inertial measurement unit on a single chip. The estimated size for this system is approximately 4 mm by 10 mm.

**Multi-Level, Planarized Polysilicon Systems-on-a-Chip**

**µEngine**

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 developed devices that overcome these issues. Our three-level polysilicon micromachining process11,12 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-reducing layer of silicon nitride is placed between the layers that form bearing surfaces. The inset (lower right) to Figure 4 illustrates a bearing formed between two layers of mechanical poly. The overall photo in Figure 4 shows two comb-drive actuators driving a set of linkages to a set of rotary gears. This engine can be rotated by applying 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 8x10⁸ revolutions. This smaller gear is shown driving a larger (1.6 mm diameter) gear13 in Figure 4. This larger gear has been driven as fast as 4800 rpm.

**µTransmission**

To increase the torque available from a rotary drive, a multi-level microtransmission has been developed.14 This transmission, shown in Figure 5, employs sets of small and large gears mounted on the same shaft that interlock with other sets of gears to transfer power while providing torque multiplication and speed reduction. The structure shown in Figure 5 couples the output gear of a microengine similar to the engine shown in Figure 4 to a rack and pinion unit that provides linear motion with high force.

**µLock**

The microengine described above has been used to drive the wheel of a pin-in-maze microcombination lock.14 As shown in Figure 6, a pin suspended on an arm driven by an electrostatic actuator is navigated through a maze cut into a wheel driven by the Sandia microengine. Correct positioning of the pin, allows rotation of the larger wheel. Multiple decision points exist in the path on the wheel. All but one path leads to a series of dead ends. A ratchet and pawl mechanism prevent backwards rotation of the large maze wheel.
Figure 5. An electrostatic microengine output gear coupled to a double-level gear train that drives a rack and pinion slider. This gear train provides a speed-reduction/torque-multiplication ratio of 9.6 to 1.

Figure 6. A pin-in-maze microcombination lock. The pin must be electrostatically deflected to traverse the maze cut into the large gear.

Summary
Sandia’s Microelectronics Development Laboratory has developed and is advancing a broad range of sensors and actuators based on polysilicon surface micromachining. A technology where micromachined devices are embedded below the surface of a wafer prior to fabrication of microelectronic devices has also been developed and applied to build a three-axis inertial measurement unit system-on-a-chip. A three-level polysilicon process enables intricate coupling mechanisms that link linear comb-drive actuators to multiple rotating gears. This technology has been applied to microengines, microtransmissions, microlocks, and micromirrors.

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References