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MICROMACHINING TECHNOLOGY FOR ADVANCED WEAPON SYSTEMS

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Jeffry J. Sniegowski
Sandia National Laboratories
Albuquerque, NM 87185-5800

Abstract

An overview of planned uses for polysilicon surface-micromachining technology in advanced weapon systems is presented. Specifically, this technology may allow consideration of fundamentally new architectures for realization of surety component functions.

Introduction

Several possibilities exist for the utilization of polysilicon surface-micromachining technology in advanced weapon systems. Typical advantages cited include the reduction of mass, volume, and possibly cost through micro-construction. In addition, it is possible to go beyond considering just the mechanical constructions and include the benefits of the integration of CMOS circuitry with the micromachined elements. Further, a real and exciting possibility exists to reconceive the means of providing the desired functions through fundamentally new architectures. Therefore, the presentation of these aspects will be illustrated with examples of current efforts to micromechanically reconstruct several elements of weapon surety components, with an overview of Sandia's novel embedded micromechanics monolithic integration process, and with brief discussions of these potential micromechanical architectures.

Fabrication Technology and Facilities

Polysilicon surface micromachining is a technology for manufacturing Micro-Electro-Mechanical Systems (MEMS) which has, as its basis, the manufacturing methods and tool sets used to manufacture the integrated electronic circuit. This section presents only a cursory overview to polysilicon surface micromachining since Howe and Muller [1] provide a basic definition for surface micromachining while Garcia and Sniegowski [2] provide a detailed description of the three-level process used to fabricate the micromechanisms illustrated. Further description of the technology including discussion of advantages to a multi-level technology, common process issues with solutions, and post-fabrication tribology issues of stiction, friction, and wear are provided by Sniegowski [3].

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. 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 polysilicon 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 simple cantilevered beams to complex systems of springs, linkages, mass elements and joints. Typical in-plane lateral dimensions can be from one micron to several hundred microns, while the film thickness are typically in the range of two to four microns. 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.

The infrastructure for the manufacture of ICs and MEMS is found in a facility such as the Microelectronics Development Laboratory (MDL) at Sandia National Laboratories. The facility 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 MEMS, in addition to the continued development of sub-micron CMOS. These other technologies benefit form the wide variety of equipment and processes in existence to support the baseline CMOS, but they must maintain a degree of compatibility with CMOS manufacturing processes so that they do not contaminate those processes.

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Microactuated Micromechanisms for Surety

One area with both new and existing weapon systems that Sandia is viewing for potential application of MEMS is weapon surety. Surety entails the safe arming, fusing, and firing of a weapon. Without proceeding in great detail, the use of miniature, light-weight MEMS components to replace suitable current surety components in existing systems or in the design of new systems while still providing the same degree of safety would allow the addition of other elements such as 'state-of-health' sensors. For example, the micromechanical miniaturization of a stronglink surety component which currently has approximately a 10 cubic cm volume will reduced to a 1 cubic cm volume.

One potential surety component, includes actuation, optical energy re-direct, and lock elements. To provide clarification, Figs. 1 through 3 are SEM images of elements fabricated in MEMS which provide these functions. These elements have been fabricated and have demonstrated the desired single-value functions.

In Fig. 1, a multilevel gear train with a 1:9.63 overall gear ratio drives a rack element to provide long linear displacement (several hundred microns). The gear unit requires the use of all three levels of mechanical polysilicon to produce the two sets of bi-level compound gears. The primary goal of the gear unit is torque multiplication of the basic microengine and has been accomplished. Thus, the microengine driven gear and rack unit provides the fundamental function of large-displacement linear actuation.

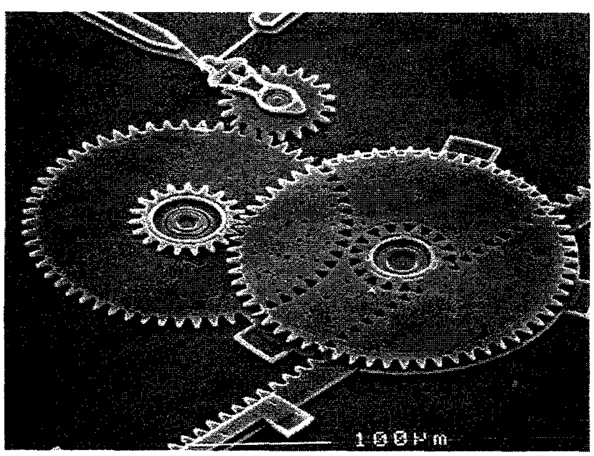

Figure 1 is an SEM of the completed gear-speed-reduction unit and linear rack. The linear speed of the rack is approximately one tenth that of the linear tooth velocity of the drive gear. The rack can be used to drive a folding mirror, for example.

For clarification, cut-out features matching the underlying gear elements results from a fabrication constraint which recently can be eliminated by the use of an IC process novel to MEMS fabrication known as Chemical-Mechanical Polishing (CMP) [4]. The gear unit does not require redesign to incorporate CMP and thus has not yet been modified. Additional description of geared mechanisms and their evolution is found in reference [5].

One application of linear actuation is demonstrated where the gear and rack unit of Fig. 1 is shown coupled to a folding mirror in Fig. 2. The folded mirror is used to redirect an optical signal.

Figure 2. SEM micrograph of the combined microengine, gear unit and rack, coupled to a folding pop-up mirror shown in the full upright position.

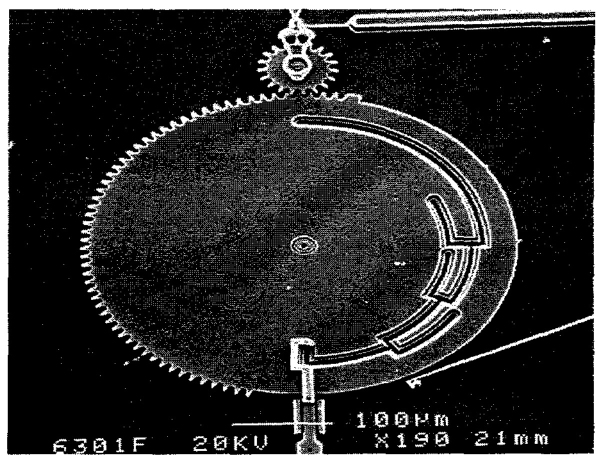

Figure 3 is an SEM of one potential discriminator design based on a pin-in-a-maze concept. The drive gear shown at the top has a 60 µm diameter and 2.5 µm thickness.

Fig. 3 is an SEM micrograph of an example lock configuration based on a pin-in-a-maze discriminator concept that has been used in a macromechanical design [6]. In Fig. 3, the entrapped pin must be guided, via the correct input signals, to allow full rotation of the element. Once the maze is successfully navigated the wheel is free to complete its rotation. Although not demonstrated by this structure, the full rotation of the wheel could be used to insert an additional critical element or unlock another structure.

Both the pin-in-maze and the gear unit are powered by an on-chip electrostatic microengine, part of which is seen in the upper portion of Figs. 1 and 3, and to the rightside of Fig. 2. The basic microengine is described in detail in [2]. The microengine and driven gears are capable of rotational speeds of up to 300,000 revolutions per minute (RPM). A lifetime of over 3.2 billion revolutions including 66,300 start/stop cycles has been demonstrated. In the case of Fig. 2, the engine has been used to cycle the folding mirror from a in-plane position to the full up-right out-of-plane position in 35 msec.

At this time, our effort is to combine an optical re-direct element as in Fig. 2 with a lock element such as in Fig. 3 in a packaged prototype. The prototype parts are in fabrication.

CMOS/Micromachine Monolithic Integration

In the MDL's thrust to support the development of advanced weapons systems which utilize micromachining, the integration of support electronics with micromechanical structures provides essential benefits. The advanced multi-level polysilicon technology developed for the surety application described above is readily applicable to the fabrication of micromechanical structures for sensing. Monolithic integration of polysilicon surface micromachined structures with driving, controlling, and signal processing electronics is appealing. The potential exists to improve the performance of micromechanical devices as well as lower the cost of manufacturing, packaging, and instrumenting these devices. This is accomplished by combining the micromechanical devices with electronics devices in the same manufacturing and packaging process.

In order to maintain modularity and overcome some of the manufacturing challenges of the CMOS-first approach to integration, we have developed a MEMS-first approach. This approach places the micromechanical devices in a shallow trench, planarizes the wafer, and seals the micromechanical devices in the trench. This allows a high-temperature anneal to be performed after the devices are embedded in the wafer but prior to microelectronics processing. This anneal stress-relieves the micromechanical polysilicon and ensures that the subsequent thermal processing associated with fabrication of the microelectronic processing does not adversely affect the mechanical properties of the polysilicon structures. These wafers with the completed, planarized micromechanical devices are then used as starting material for conventional CMOS processes. Further description of the integration technology, the refinements to the technology, and wafer-scale parametric measurements of device characteristics is presented in [7].

Integrated High-g Accelerometer

One example of a monolithically integrated sensor being developed specifically for a weapon system is shown in Fig. 4. Performance of this first-generation integrated sensor will be presented at a later date. This example illustrates both the extreme environments encountered by a weapon and the capability of the integrated technology to produce sensors suitable to that range.

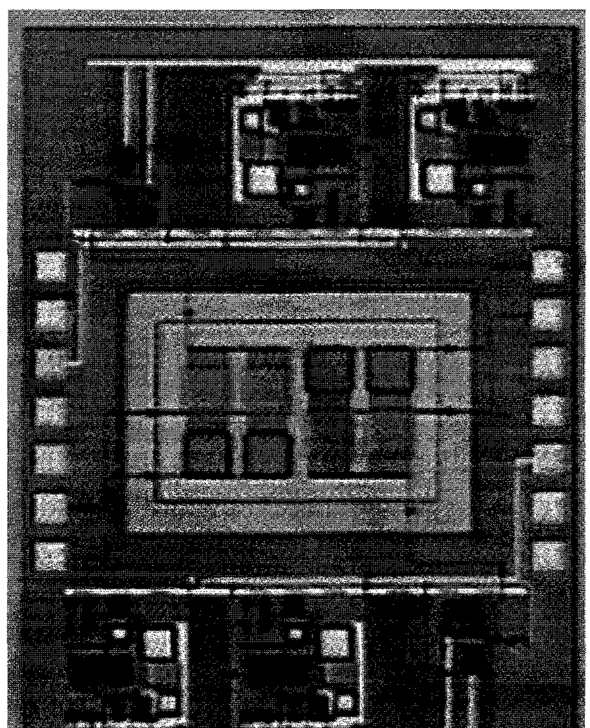

Figure 4. Photograph of a high-g accelerometer with the mechanical elements in the center surrounded by the signal processing electronics. Die size is approximately 0.2 cm x 0.3 cm.

To produce a sensor of this desired size, monolithic integration is necessary for the following reasons. The accelerometer uses capacitive transduction and the maximum proof mass displacement is one micron. At these dimensions, sensing a 50,000 g signal through a one micron displacement corresponds to 500g/fF sensitivity. For reasonable resolution, measurement capability into the attoFarad level is necessary. This can only be accomplished by on-chip signal processing. Excessive parasitic capacitance precludes the use of off-chip electronics.

Summary

Micromachining technology and the integration of micromachining technology with electronic circuitry provides a means to miniaturize conventional macromechanical designs of various weapon components and potentially provides an avenue for novel architecture.

Acknowledgments

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