CONF-9609185--8 SAND96-1895C

MICROMACHINED SILICON SEISMIC ACCELEROMETER DEVELOPMENT

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JUL 30 1996
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Sponsored by U.S. Department of Energy,
Comprehensive Test Ban Treaty Research and Development Program, ST4850

ABSTRACT

Batch-fabricated silicon seismic transducers could revolutionize the discipline of seismic monitoring by providing inexpensive, easily deployable sensor arrays. Our ultimate goal is to fabricate seismic sensors with sensitivity and noise performance comparable to short-period seismometers in common use. We expect several phases of development will be required to accomplish that level of performance. Traditional silicon micromachining techniques are not ideally suited to the simultaneous fabrication of a large proof mass and soft suspension, such as one needs to achieve the extreme sensitivities required for seismic measurements. We have therefore developed a novel "mold" micromachining technology that promises to make larger proof masses (in the 1-10 mg range) possible. We have successfully integrated this micromolding capability with our surface-micromachining process, which enables the formation of soft suspension springs. Our calculations indicate that devices made in this new integrated technology will resolve down to at least sub-μG signals, and may even approach the 10^{-10} $G/\sqrt{\text{Hz}}$ acceleration levels found in the low-earth-noise model.

KEY WORDS

Silicon micromachining, microelectromechanical systems, mold micromachining, micromolding, seismic transducers, accelerometers, seismometers, CTBT.

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1. INTRODUCTION AND OBJECTIVES

One of the factors inhibiting the effort to collect seismic data for Comprehensive Test Ban Treaty (CTBT) monitoring is the sheer cost, including both the system cost and the deployment cost, of current seismic transducers. Our motivation in pursuing microminiature silicon seismic transducers is twofold. First, such devices would be much less expensive to manufacture than current seismometers, since they could be batch-fabricated in much the same way that electronic integrated circuits are. Moreover their small size would make deployment easier and cheaper as well. Our ultimate goal is to fabricate seismic sensors with sensitivity and noise performance comparable to short-period seismometers in common use. We expect several phases of development will be required to accomplish that level of performance.

We have calculated the best-case performance possible for a seismic accelerometer fabricated in Sandia's experimental "mold-micromachining" technology to be at or very near our most ambitious target specifications. Accordingly, we have actively pursued development of this new micromachining technology, and have this year successfully achieved integration of a micro-molded proof mass with compliant surface-micromachined suspension. In this paper we present the design of a prototype device with sub-micro*G* theoretical resolution, and the development of the new fabrication technology required to manufacture these devices. At the symposium we will also present the latest test results from the prototype devices.

2. PROTOTYPE DESIGN

Because the principal axis of interest for seismic measurements is the vertical one, our basic accelerometer design consists of an unbalanced "teeter-totter" platform suspended on opposite sides by two small flexures (Figure 1). This design is a variation on the common "pendulum" design for existing seismic accelerometers, modified to allow differential capacitive pick-offs to be placed to either side of the flexures. We have chosen capacitive pick-offs rather than magnetic coil-based transducers because it is virtually impossible to make a coil in a micromachining process, while parallel-plate capacitors with very small, uniform gaps are a natural in this technology. We also discarded a third possibility, electron tunneling, which has been employed in sensitive accelerometer designs by another micromachining group,[1] because of reliability concerns and because of the $1/f$ noise which limits the performance of tunneling sensors at the very low frequencies which are of interest in seismic monitoring.

The signal-to-noise ratio for the motion of an accelerometer versus thermal-mechanical noise (electronic noise is not usually the limiting factor for seismic transducers) is given by

$$S/N = \sqrt{\frac{a_s^2 m Q}{4\,k_B T \omega_o}},$$

where a_s is the acceleration signal, m the proof mass, Q the so-called "quality factor" (a measure of damping), k_B is Boltzmann's constant, T the absolute temperature in Kelvin, and $w_o = 2\pi f_o$ the natural frequency of the mechanical system.[2] If we insert 10^{-10} $G/\sqrt{Hz}$ for a_s, and the maximum possible Q of 30,000 (corresponding to the intrinsic material damping of a silicon device in an evacuated package), we obtain a set of pairs of $\{m, f_o\}$ which will give an adequate signal-to-noise ratio. From among these, a potentially feasible pair is $m \geq 10$ mg and $f_o \leq 1$ Hz. In order to achieve these values, it will be necessary to develop a new silicon micromachining technology, as current technologies cannot deliver the combination of large (on this scale at least) proof mass and soft suspension. We have invented a novel fabrication process which addresses these issues — this new "mold" process is described below.

3. SILICON MICROMACHINING TECHNOLOGIES

Silicon micromachining technologies can be divided into three categories — so-called "bulk," "surface," and "mold" micromachining. "Bulk" micromachining generally refers to processes involving wet chemical etching of structures formed out of the silicon substrate and so is limited to fairly large, crude structures. "Surface" micromachining allows patterning of thin films of polysilicon and other materials to form intricate but essentially two-dimensional layered parts (since the thickness of the parts is limited by the thickness of the deposited films). In "mold" micromachining, the mechanical part is formed by filling a mold which was defined by photolithographic means. Historically micromachining molds have been formed in some sort of photopolymer, be it with x-ray lithography ("LIGA") or more conventional UV lithography, with the aim of producing piece parts. Recently, however, several groups including ours at Sandia have independently come up with the idea of forming the mold for mechanical parts by etching into the silicon substrate itself. The following is a quick review of these three micromachining methods intended to clarify the approaches we have taken in fabricating seismic sensor prototypes. Note that the references given here are only examples and are not by any means intended to be a complete survey of the literature.

3.1 Bulk micromachining

The term "bulk" micromachining literally refers to the process of making a mechanical structure out of the bulk material (i.e. the single-crystal silicon substrate). Generally the mechanical structure is formed either by doping-selective[3] or crystallogaphic[4] wet chemical etching. These processes are relatively large-scale and crude compared to the sub-micron photolithographic processes common in microelectronic fabrication, with dimensional variations on the microns to hundreds-of-microns scale. A subcategory of bulk micromachining which offers finer dimen-

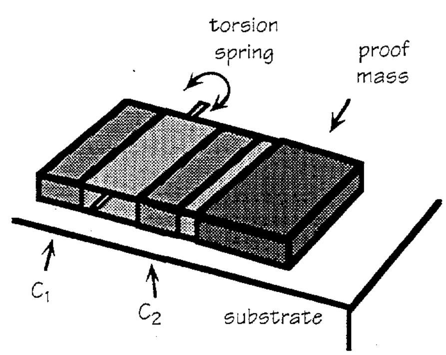


Figure 1. "Teeter-totter" seismic sensor concept.

sional control is dry etching of mechanical structures — again, the part is formed from the single-crystal silicon substrate itself.[5] One of the major advantages of bulk micromachining is that it is relatively easy to fabricate large masses (for accelerometers, for example), but, on the other hand, delicate, sensitive suspensions are difficult to realize. Also, bulk micromachining processes are not particularly compatible with electronics, simply because they aren't planar.

We rejected bulk micromachining as a fabrication strategy for seismic sensors, even though the most sensitive silicon accelerometers to date have been made this way,[1] for several reasons. First, we do not have a mature bulk-micromachining technology at Sandia, and therefore making the prototypes using bulk processes would not leverage well with our other projects. Second, bulk micromachining does not lend itself to monolithic integration with electronics and we are convinced that integrated amplifiers and servo electronics will be necessary in order to achieve the sensitivities required for treaty monitoring.

3.2 Surface micromachining

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 Figure 2, holes 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.

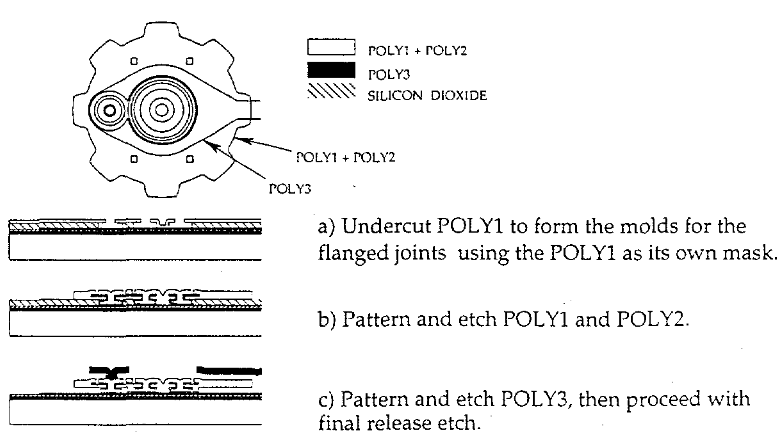


Figure 2: Example surface-micromachining process.[6] These are cross-sections through essential elements of the Sandia microengine gear and joints taken at three stages of completion.

Because surface micromachining takes advantage of the advanced manufacturing processes developed in the microelectronics fabrication industry, it offers the same high degree of dimensional control found in electronic integrated circuit fabrication, and is the micromachining method most compatible with monolithically integrated electronics.[7] The planarity which makes surface-micromachined parts relatively easy to integrate with microelectronics, however, is also the major limitation of surface micromachining — that is, surface-micromachined parts are essentially two-dimensional (since the thickness of the parts is limited by the thickness of the deposited films), and therefore relatively light and compliant. (Typical masses for surface-micromachined components are in the μg range and it is difficult to achieve natural frequencies below 1 kHz.) Sandia's three-level polysilicon process is the world's most sophisticated surface-micromachining technology, and offers integrated electronics as well as complex mechanical parts. We are utilizing surface-micromachining to fabricate the suspension for our seismic transducers.

3.3 Mold micromachining or Micromolding

The principal advantage of all mold micromachining processes are that they make it possible to fabricate high-aspect-ratio parts (i.e. thick relative to surface dimensions). Mold micromachining has generally been used to manufacture piece parts (e.g. gears, etc.), although micromachined structures formed with thick photo-sensitive polymer molds have also been integrated with previously fabricated electronic circuits. Variations on the mold concept include, on the one hand, the well-known "LIGA" process, in which lithography is used directly to form a photoresist mold, and, on the other hand, silicon mold processes, in which the mold is formed by etching into the silicon substrate.

3.3.1 "LIGA" and "LIGA-like" processes

"LIGA" is a German acronym which refers to "lithography, electroplating, and injection molding". The original LIGA process, while it achieves impressive aspect ratios,[8] has only seen scattered application because it requires specialized x-ray lithography equipment. "LIGA-like" processes include ones where the more common UV-exposed photoresist is used instead. These "LIGA-like" processes allow fabrication of thicker parts than can be made using surface micromachining, but are generally limited to much less extreme aspect ratios than the original LIGA process.[9] Both the original LIGA process and the "LIGA-like" processes lend themselves primarily to the fabrication of piece parts which require subsequent assembly into a microelectromechanical system.

3.3.2 Silicon mold processes

The basic concept behind silicon mold processes is that the mold for a micromechanical part is formed by etching into the silicon substrate (Figure 3). Silicon mold processes thus take advantage of the fact that, by etching a high-aspect-ratio mold (that is, one which is much deeper than it is wide) and filling it with a conformal thin film, one can form a mechanical structure that is much thicker than the maximum thickness of the deposited film itself. Our group at Sandia is one of three research groups which have independently conceived of the silicon mold idea and have been pursuing variants on the basic process.[10]

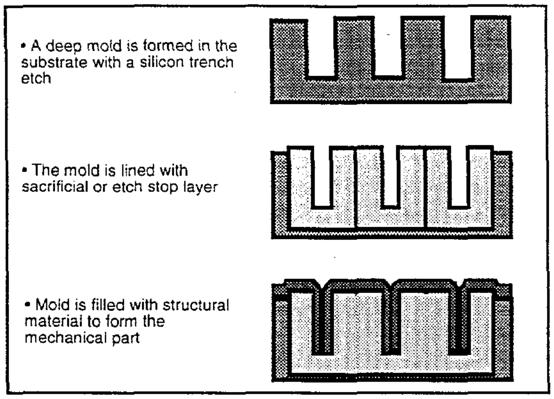


Figure 3. Generalized silicon mold process.

3.3.3 The Sandia mold micromachining process

The first step in the Sandia mold process is to etch the mold pattern into the substrate using a "deep trench" reactive-ion-etching process. The silicon pattern is then transformed into a mold in one of several ways. For example, if the structure will be formed of polysilicon and "released" with a hydrofluoric acid etch, the mold is oxidized at this point. It is also possible to remove the silicon mold by wet etching the silicon, in which case the mold is completed instead by depositing an etch stop layer. The commonality in both cases is that, in the end, the mold-micromachined parts are anchored to the substrate and released in place, like surface-micromachined parts — the mold is not reused. After the mold is formed, it can be filled with any of a number of materials, including most of the thin films common in the semiconductor industry (doped or undoped polysilicon, silicon nitride, tungsten, etc.), as well as plated metals. The wafer is then planarized by an etchback or chemical-mechanical polish (CMP) process. At this point, assuming materials compatibility, it can be taken through a surface-micromachining or electronic integrated circuit fabrication process (or both). Once all the processing is complete, the mechanical parts are released so that they are free to move relative to the substrate.

4. INTEGRATED MICROMOLDING/SURFACE-MICROMACHINING PROCESS

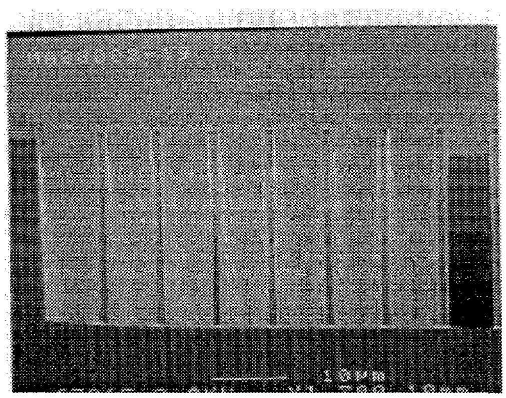
In the past year, we have successfully demonstrated the integration of micromolded silicon proof masses with surface-micromachined suspension springs. Fig. 4 details the integrated process. First, the proof mass mold is formed by etching into the substrate (Fig. 4a), and then oxidizing the mold (Fig. 4b). The pillars, which are spaced throughout the mold on a rectangular grid, are oxidized entirely, so that they will dissolve completely in the final hydrofluoric acid release etch. The mold is then filled with chemical-vapor-deposited (CVD) polycrystalline silicon (Fig. 4c), and planarized with CMP (Fig. 4d). At this point, the planarized wafers are run through our standard surface-micromachining process, which includes the deposition of a layer of sacrificial oxide, patterning of vias through the sacrificial layer to anchor the surface polysilicon parts of the structure (the suspension springs and pickoff/force-feedback contacts) to the substrate, and finally deposition and patterning of the surface polysilicon structures. A scanning-electron micrograph of the finished, partially-released accelerometer structure showing the molded proof mass and surface-micromachined suspension spring and contacts is shown in Fig. 5.

5. SPECIAL INSTALLATION FEATURE OF THE SEISMIC SENSOR PROTOTYPE

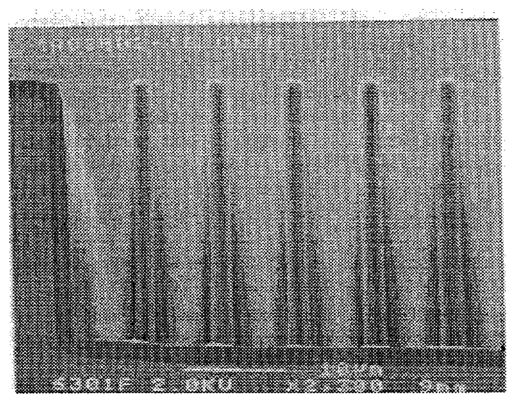
The seismic sensor prototype features polysilicon fuses, essentially additional suspension springs formed at regular intervals around the perimeter of the proof mass to hold it in place during the wet-chemical release etch and drying processes. These fuses are blown with the application of short current pulses after the device has completed the manufacturing process. This feature would enable the sensitive transducer to be packaged and installed in the field through high *G*-forces without sustaining any damage, and then "unlocked" once the transducer package is in place. We expect that this capability would enable low-cost installation alternatives.

6. FUTURE PLANS

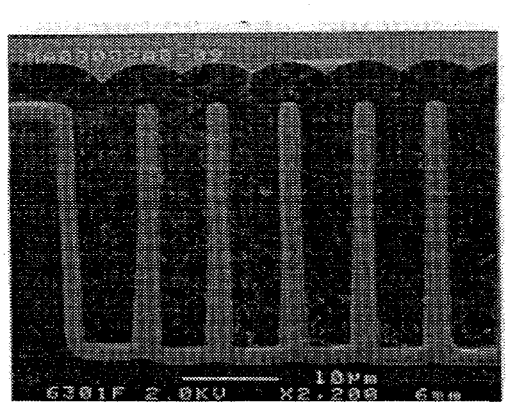
One of the greatest challenges in the micromachining field is to achieve structures which have been "released"completely, that is structures which are free to move relative to the substrate. The agitation of the wet etch processing tends to break delicate suspensions and solvent residue tends to cause sticking or excessive friction (the combination is popularly called "stiction"). Our future plans for this project include several strategies for implementing a "stiction"-free release of the molded seismic sensor prototypes, including treating the structures with polymeric surface layers



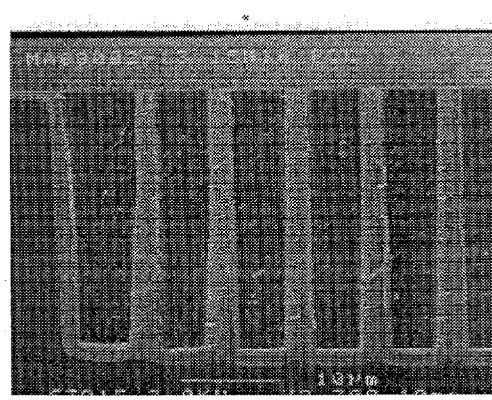
← Figure 4a. SEM photo of etched proof mass mold (in cross-section).



→ Figure 4b. SEM photo of oxidized proof mass mold (in cross-section).



← Figure 4c. SEM photo of etched proof mass mold filled with polysilicon (in cross-section).



→ Figure 4d. SEM photo of planarized polysilicon proof mass (in cross-section).

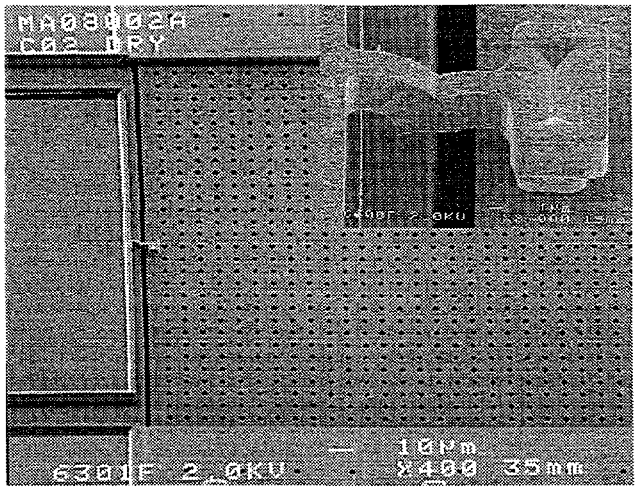


Figure 5: Completed silicon seismic accelerometer prototype manufactured in Sandia's integrated micromolding / surface-micromachining fabrication process. Inset shows close-up of surface-micromachined suspension spring.

to make them hydrophobic[12], and displacing the liquid under the structures with a superfluid (supercritical CO_2)[13]. Both of these methods have been shown to be successful in preventing stiction in other micromachined devices. Once we have completely released devices, we will test the devices, quantify their performance, and redesign them as needed to approach the requirements for a CTBT seismic sensor.

7. SIGNIFICANCE FOR CTBT

Inexpensive micromachined silicon seismic sensors could revolutionize the seismic data-gathering process. The cost savings realized by a micromachined design would result not only from the reduced cost of the sensor itself, but also from lower installation and maintenance costs. A borehole system using current sensor and electronics technologies can be as heavy as 200 pounds (90 kg) and its installation requires a drilling rig. The expense of installing and maintaining an array of such sensors often far outweighs the cost of the sensors themselves. A small, low-cost sensor could also make portable/disposable systems for both cooperative and non-cooperative seismic monitoring viable.

The capabilities and cost of the proposed seismic sensor would also make it attractive for related commercial applications such as low-cost, sensitive earthquake monitors and sensors for oil and gas exploration. The existence of large commercial markets for the sensor would drive manufacturing volumes up and costs down and would attract the interest of commercial sensor manufacturers. The CTBT community, which is in itself a relatively small market, would then benefit from association with these larger commercial applications.

ACKNOWLEDGMENTS

The authors would like to acknowledge the process engineering and fabrication staff of the Microelectronics Development Laboratory for fabricating the prototype seismic sensors. This work was performed at Sandia National Laboratories and supported by the U. S. Department of Energy under contract # DE-AC04-94AL85000.

NOTES AND REFERENCES

1. T. W. Kenny, S. B. Waltman, J. K. Reynolds, and W. J. Kaiser, "Micromachined silicon tunnel sensor for motion detection," Applied Physics Letters, Vol. 58, No. 1, Jan 1991, pp. 100-102.

2. T. B. Gabrielson, "Mechanical-Thermal Noise in Micromachined Acoustic and Vibration Sensors," IEEE Transactions on Electron Devices, Vol. 40, No. 5, May 1993, pp 903-909.

   This equation, strictly speaking, does not hold for the torsional motion of our device, but it turns out that the results one obtains by substituting in the torsional equivalents (moment of inertia for mass, etc.) are to the first order indistinguishable from the linear motion equation given here.

3. L. Spangler and K. D. Wise, "A New Silicon-on-glass Process for Integrated Sensors," IEEE Sensor and Actuator Workshop, Hilton Head, SC, pp. 140-142, June, 1988.

4. K. E. Petersen, "Silicon as a Mechanical Material," Proc. IEEE, vol. 70, no. 5, pp. 420-457, May, 1982.

5. Examples of bulk micromachining using dry etching:

   W.H. Juan and S. W. Pang, "A Novel Etch-Diffusion Process for Fabricating High Aspect Ratio Si Microstructures," 8th International Conference on Solid-State Senosrs and Actuators, Stockholm, Sweden, June 25-29, 1995, pp. 560-563.

   Y. Xu, S. A. Miller, and N. C. MacDonald, "Microelectromechanical Scanning Tunneling Microscope", 8th International Conference on Solid-State Sensors and Actuators, Stockholm, Sweden, June 25-29, 1995, pp. 640-643.

6. The Sandia tri-level polysilicon surface-micromachining technology has been described in

   J. J. Sniegowski and E. J. Garcia, "Microfabricated Actuators and their Application to Optics," Proc. SPIE vol. 2383, pp. 46-64.

   For an earlier review of surface micromachining:

   R. T. Howe, "Surface micromachining for microsensors and microactuators," J. Vac. Sci. Technol. B, vol. 6, no. 6, pp. 1809-1813, 1988.

7. T. A. Core, W. K. Tsang, and S. J. Sherman, "Fabrication technology for an integrated surface-micromachined sensor," Solid State Technology, vol. 36, no. 10, pp. 39+, 1993.

8. H. Guckel, T. Earles, J. Klein, D. Zook, and T. Ohnstein, "Electromagnetic Linear Actuators with Inductive Position Sensing for Micro Relay, Micro Valve and Precision Positioning Applications," 8th International Conference on Solid-State Sensors and Actuators, Stockholm, Sweden, June 25-29, 1995, pp. 324-327.

   E. W. Becker, W. Ehrfeld, P. Hagman, A. Maner, and D. Münchmeyer, Microelectronic Engineering, vol. 4,) pp. 35-56, 1986.

9. Examples of "LIGA-like" processes:

   M. W. Putty and K. Najafi, "A Micromachined Vibrating Ring Gyroscope," 1994 Solid-State Sensor and Actuator Workshop, Hilton Head, SC June 13-16, 1994, pp. 213-220.

   A. B. Frazier and M. G. Allen, "Uses of Electroplated Aluminum in Micromachining Applications," 1994 Solid-State Sensor and Actuator Workshop, Hilton Head, SC June 13-16, 1994, pp. 90-94.

10. Other examples of silicon mold micromachining:

   C. G. Keller and R. T. Howe "Hexsil Bimorphs for Vertical Actuation," pp. 99-102, and "Nickel-Filled HEXSIL Thermally Actuated Tweezers," pp. 376-379, 8th International Conference on Solid-State Sensors and Actuators, Stockholm, Sweden, June 25-29, 1995.

   C. Keller and M. Ferrari, "Milli-Scale Polysilicon Structures," 1994 Solid-State Sensor and Actuator Workshop, Hilton Head, SC June 13-16, 1994, pp. 132-137.

   A. Selvakumar and K. Najafi, "High Density Vertical Comb Array Microactuators Fabricated Using a Novel Bulk/Polysilicon Trench Refill Technology," 1994 Solid-State Sensor and Actuator Workshop, Hilton Head, SC June 13-16, 1994, pp. 138-141.

11. C. G. Keller and R. T. Howe "Hexsil Bimorphs for Vertical Actuation," pp. 99-102, and "Nickel-Filled HEXSIL Thermally Actuated Tweezers," pp. 376-379, 8th International Conference on Solid-State Sensors and Actuators, Stockholm, Sweden, June 25-29, 1995.

12. M.R. Houston, R. Maboudian, and R. T. Howe, "Self-assembled monolayer films as durable anti-stiction coatings for polysilicon microstructures," 1196 Solid-State Sensor and Actuator Workshop, Hilton Head, SC, June 2-6, 1996, pp. 42-47.

13. G. T. Mulhern, D. S. Soane, and R. T. Howe, "Supercritical carbon dioxide drying of microstructures," The 7th International Conference on Solid-State Sensors and Actuators, Transducers '93, pp. 296-299, 1993.