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Integrated Mold / Surface-Micromachining Process

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ABSTRACT

We detail a new monolithically integrated silicon mold/surface-micromachining process which makes possible the fabrication of stiff, high-aspect-ratio micromachined structures integrated with finely detailed, compliant structures. An important example, which we use here as our process demonstration vehicle, is that of an accelerometer with a large proof mass and compliant suspension. The proof mass is formed by etching a mold into the silicon substrate, lining the mold with oxide, filling it with mechanical polysilicon, and then planarizing back to the level of the substrate. The resulting molded structure is recessed into the substrate, forming a planar surface ideal for subsequent processing. We then add surface-micromachined springs and sense contacts. The principal advantage of this new monolithically integrated mold/surface-micromachining process is that it decouples the design of the different sections of the device: in the case of a sensitive accelerometer, it allows us to optimize independently the proof mass, which needs to be as large, stiff, and heavy as possible, and the suspension, which needs to be as delicate and compliant as possible. The fact that the high-aspect-ratio section of the device is embedded in the substrate enables the monolithic integration of high-aspect-ratio parts with surface-micromachined mechanical parts, and, in the future, also electronics. We anticipate that such an integrated mold/surface micromachining/electronics process will offer versatile high-aspect-ratio micromachined structures that can be batch-fabricated and monolithically integrated into complex microelectromechanical systems.

KEY WORDS

Micromachined accelerometers, silicon micromachining, microelectromechanical systems, surface micromachining, mold micromachining, LIGA, reactive ion etching (RIE), chemical-mechanical polishing (CMP), mechanical polysilicon.

1. INTRODUCTION

Micromachining is often divided into two categories — bulk and surface micromachining. "Bulk" micromachining generally refers to the etching of three-dimensional structures out of the silicon substrate. "Surface" micromachining involves patterning of thin films of polysilicon and other materials to form essentially two-dimensional layered parts (since the thickness of the parts is limited by the thickness of the deposited films). In addition to these two types of micromachining there is in fact a third type of micromachining as well, namely "mold" micromachining, in which the 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 National Laboratories have independently come up with the idea of forming the mold for mechanical parts by etching into the silicon substrate itself.

In Sandia's mold process, the mold is recessed into the substrate using a deep silicon trench etch, lined with a sacrificial or etch-stop layer, and then filled with any of a number of mechanical materials. The completed structures are not ejected from the mold to be used as piece parts — rather, the mold is dissolved from around selected movable segments of the parts, leaving the parts anchored to the substrate. Unlike surface-micromachined parts, the thickness of the molded parts is limited by the depth of the trench etch (typically 10-50 μm) rather than the thickness of deposited polysilicon (typically ≈2 μm). The capability of fabricating thicker (and therefore much stiffer and more massive) parts is critical for motion-sensing structures involving large gimballed platforms, proof masses, etc. At the same time, the planarized mold technology enables the subsequent fabrication of surface-micromachined features (for example flexible springs and flexures) — much finer than those possible with bulk processes. In this paper we will detail the fabrication process for an accelerometer with molded polysilicon proof mass and surface-micromachined suspension.

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In order to highlight the merits of the Sandia integrated mold/surface-micromachining process, it is useful first to consider the relative strengths and weaknesses of the various micromachining approaches. Note that the references given here are only examples and are not by any means intended to be a complete survey of the literature.

1.1 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[1] or crystallogaphic[2] 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 dimensional control is dry etching of mechanical structures — again, the part is formed from the single-crystal silicon substrate itself.[3] 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.

1.2 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 1, 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.

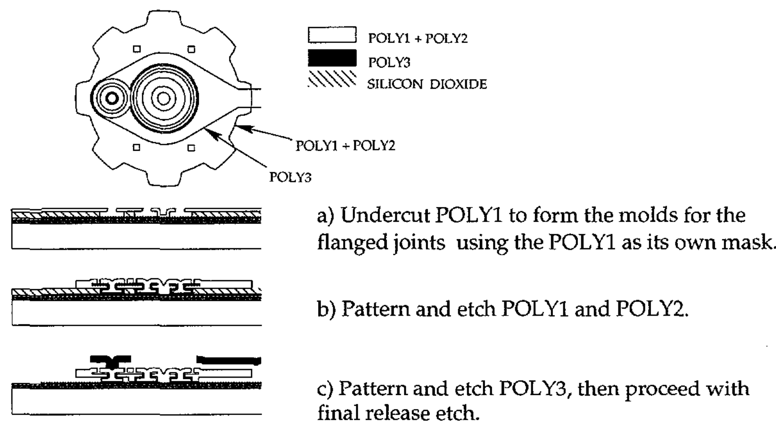

Figure 1: Example surface-micromachining process.[4] These are cross-sections through essential elements of the Sandia microengine gear and joints taken at three stages of completion.

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 integated circuit fabrication, and is the micromachining method most compatible with integrated electronics.[5] 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.

1.3 Mold micromachining

We are using "mold micromachining" to refer to micromachining processes in which a mold is formed in some way and then the mechanical structure is made by filling that mold. 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,[6,7] in which lithography is used directly to form a photoresist mold, and, on the other hand, the Berkeley "HEXSIL" process,[8] the Michigan "trench-refill" process,[9] and the Sandia mold process,[10] in which the mold is formed by etching into the silicon substrate.

1.3.1 "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,[6] 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.[7] 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.

1.3.2 Silicon mold processes

The basic concept behind all three of the silicon mold processes described in this section is that the mold for a micromechanical part is formed by etching into the silicon substrate (Figure 2). All three 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.

The so-called "HEXSIL" process, developed at UC Berkeley,[8] consists of forming a mold by sawing or reactive-ion etching into the silicon substrate, lining the mold with deposited oxide, and then filling it with polysilicon, nickel, and/or silicon nitride. The principal aim of the process is, like "LIGA," to fabricate a reusable mold for piece parts. Since the molded "HEXSIL" part is recessed into the silicon substrate, it is possible to integrate a "HEXSIL" part with electronics, although to do so the Berkeley concept requires bonding another single-crystal substrate on top of the mold.

Selvakumar and Najafi at the University of Michigan have integrated a silicon mold process (they call it "trench-refill") with bulk micromachining.[9] Again the etched silicon mold is lined with deposited oxide and then filled with polysilicon. The substrate is then removed with a wet chemical etch to release the molded part.

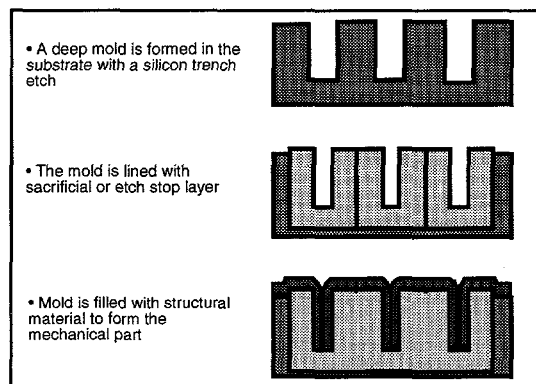

Figure 2. Generalized silicon mold process.

The independently invented Sandia mold process[10] is similar to the "HEXSIL" and Michigan processes in that the mold is formed by etching into the substrate. The goal of the process, however, is monolithic integrability of the molded high-aspect-ratio parts with surface micromachining and microelectronics, and the process flow described below consequently differs in important respects from the other silicon mold processes.

2. THE SANDIA MOLD MICROMACHINING PROCESS FLOW

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 in HF, the mold is oxidized at this point. It is also possible to release the structure by wet etching the silicon from the back side of the wafer, in which case the mold is completed instead by depositing an etch stop layer. The commonality in both cases (i.e. oxide-etch release or silicon-etch release) is that, in the end, the mold-micromachined parts are anchored to the substrate and released in place — 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, CVD tungsten, etc.), as well as plated metals. The wafer is then planarized by a plasma 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. Note that many variations on this basic silicon mold concept are possible, as we have reported previously[10] — but for the integrated mold/surface micromachining demonstration we will be using just one particular version of the Sandia mold process, in which oxide is used for the release material and polysilicon for the fill material.

3. FABRICATION OF A HIGH-ASPECT-RATIO MOLDED POLYSILICON PROOF MASS

To fabricate a polysilicon proof mass for a micromachined accelerometer, we oxidized a trench-etched mold, and filled it with mechanical polysilicon. Figure 3 shows the etched mold before and after oxidation. In order to form this mold, we used a SF_6/O_2 etch chemistry in an electron cyclotron resonance (ECR) reactive-ion etcher to etch pillars roughly two microns in diameter and about thirty microns tall out of the silicon substrate. We then oxidized the wafer to an oxide thickness of two microns. Finally, we filled the mold with a 4.5-micron film of mechanical polysilicon and planarized the wafer. We developed both plasma etchback and chemical-mechanical polishing (CMP) processes to planarize the structures. Figure 4 shows a polysilicon proof mass before and after CMP planarization. The planarized structure is now ready to be integrated with surface-micromachined suspension springs and sense contacts before being released in a hydrofluoric acid etch.

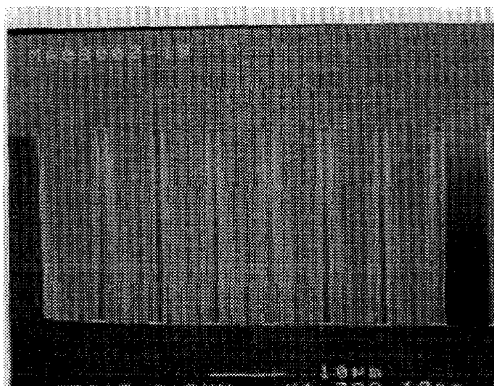

Figure 3a: ≈30 μm-deep mold for proof mass.

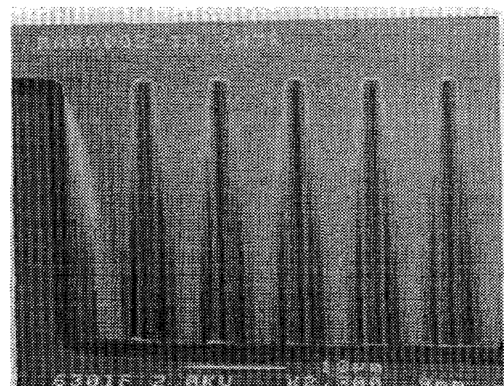

Figure 3b: Mold after oxidation.

4. INTEGRATION OF THE MOLDED PROOF MASS WITH SURFACE-MICROMACHINED SPRINGS

After the proof mass was planarized, we deposited sacrifical oxide and mechanical polysilicon layers using a traditional surface-micromachining process in order to form the suspension for the proof mass. Figure 5 shows a detail of a molded polysilicon proof mass showing one of the surface-micromachined polysilicon springs before the release etch, and a similar spring after the release etch. This particular proof mass was planarized with a blanket plasma etchback rather than CMP (hence the slightly nonplanar topography). The fact that we have fabricated the high-aspect-ratio proof mass and the surface-micromachined

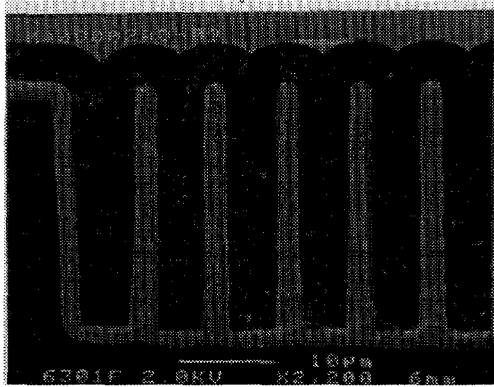

Figure 4a. Proof mass mold filled with polysilicon.

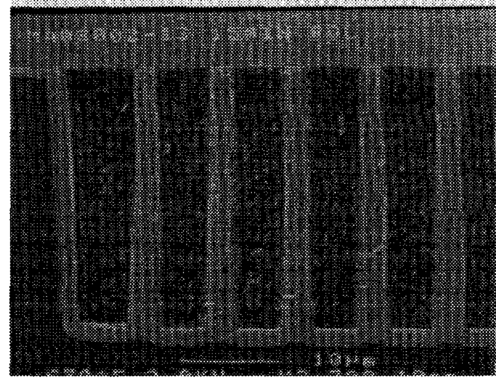

Figure 4b. Polysilicon proof mass after CMP planarization

suspension separately decouples the design parameter of the size of the proof mass from that of the softness of the suspension, introducing a critical new degree of freedom into the design of sensitive micromachined accelerometers.

5. INTEGRABILITY WITH MICROELECTRONICS

The foregoing example demonstrates the integrability of the Sandia silicon mold-micromachining process with subsequent surface-micromachining. Similarly, since the molded parts are countersunk into the substrate, the mold-micromachining process can also be integrated with subsequent microelectronic fabrication processes. We anticipate that such an integrated mold/surface micromachining/electronics process will offer versatile high-aspect-ratio micromachined structures that can be batch-fabricated and monolithically integrated into complex microelectromechanical systems.

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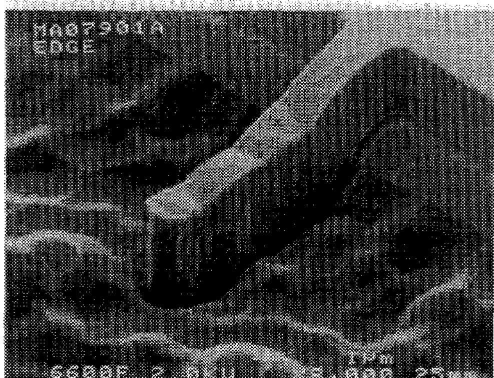
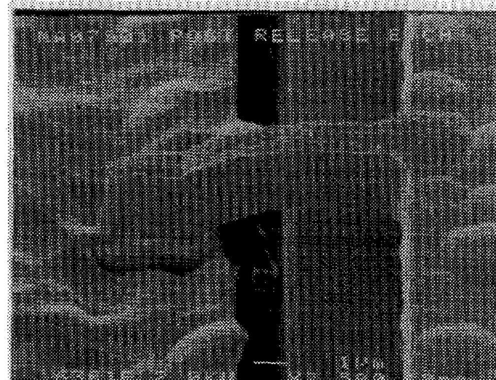


Figure 5a. Molded proof mass with surface-micromachined spring before release etch. The poly spring is ≈1 µm wide and 2.25 µm thick.



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