MULTI-LEVEL POLYSILICON SURFACE-MICROMACHINING TECHNOLOGY: APPLICATIONS AND ISSUES

Jeffry J. Sniegowski

Sandia National Laboratories
Integrated Micromechanics, Microsensors, & CMOS Technology Department
P.O. Box 5800
Albuquerque, NM 87185-1080
USA
505/844-2718, 505/844-2991 FAX, sniegojj@smtplink.mdl.sandia.gov

ABSTRACT

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 paper describes a three-level mechanical-polysilicon surface-micromachining technology and includes a discussion of the advantages of this level of process complexity along with issues which affect device fabrication and performance. Historically, the primary obstacles to multi-level polysilicon fabrication were related to the severe wafer topography generated by the repetition of film depositions and etching. The introduction of Chemical Mechanical Polishing (CMP) to surface micromachining has largely removed these issues and opened significant avenues for device complexity. Several examples of three-level devices with the benefits of CMP are presented.

Of primary hindrance to the widespread use of polysilicon surface micromachining, and in particular microactuation mechanisms, are issues related to the device surfaces. The closing discussion examines the potential of several latter and post-fabrication processes to circumvent or to directly alleviate the surface problems.

INTRODUCTION

The intent of this paper is to overview our technology of multi-level polysilicon surface micromachining, to present examples of devices which fully utilize this level of complexity, and to discuss what we believe to be significant issues which are not fully resolved.

Following this intent, the paper consists of four sections. The first is an introduction and description of multi-level polysilicon surface micromachining and its potential benefits. Specifically, the inclusion of a third deposited layer of mechanical polysilicon greatly extends the degree of complexity available for micromechanism design.

The second section introduces wafer planarization by CMP as a process tool for surface micromachining. Planarization by CMP removes the major process impediments encountered when processing multi-level surface micromachining. CMP also provides an avenue for a novel technique for monolithic integration of circuitry with the micromachines. For the integration, we have developed a novel micromechanics-first approach which embeds the micromechanical devices below the surface of a wafer prior to the microelectronics fabrication. The fully planarized wafer presents itself to the subsequent circuit process as a blank wafer with only alignment marks to the embedded micromechanics.

The third section presents examples of actuated geared micromechanisms which require the multi-level fabrication process. Recent successes with actuation mechanisms coupled to external devices are illustrated.

Polysilicon surface micromachining fabrication technology has reached a level where many device designs, for the most part, can be embodied in the technology to produce a mechanical construct which provides the desired function. When designed properly, the fabricated mechanical element, if free to operate, will produce the desired function. However, one set of issues which can hinder or prevent operation are related to the post-fabricated device surfaces. These surface issues; namely, stiction, friction, and wear, are emphasized in the final section as a major hindrance to realizing the full potential of surface micromachined devices. Stiction is the term used to describe the sticking and accompanying high static friction often encountered with MEMS devices. Alley et al. (1992) and Legtenberg, et al. (1994) provide thorough discussion of stiction and mechanisms for its cause.

POLYSILICON SURFACE MICROMACHINING TECHNOLOGY

This section presents only a cursory introduction to polysilicon surface micromachining since Howe and Muller (1983) provide a basic definition for surface micromachining while Garcia and Sniegowski (1995) provide a detailed description of the three-level process. An argument for extension to the three-level complexity follows the brief introduction.

Surface micromachining uses the planar fabrication techniques common to the microelectronic circuit fabrication industry to manufacture micromechanical devices. The standard building-block

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process consists of depositing and photolithographically patterning alternate layers of low-stress polycrystalline silicon and sacrificial silicon dioxide. As shown in Fig. 1, 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. 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.

POLY1 + POLY2
POLY3
SILICON DIOXIDE

POLY1 + POLY2
POLY3

a) Undercut POLY1 to form the molds for the flanged joints using the POLY1 as its own mask.

b) Pattern and etch POLY1 and POLY2.

c) Pattern and etch POLY3, then proceed with final release etch.
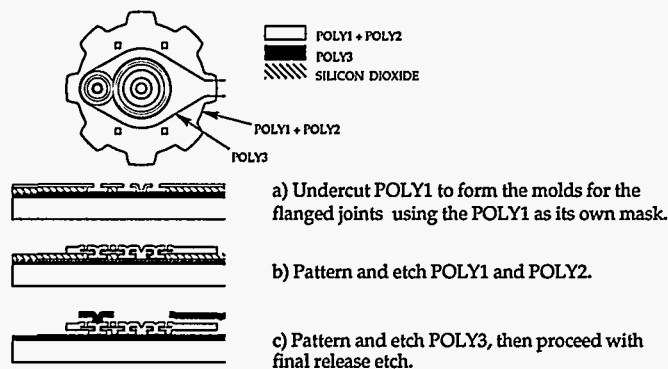
FIG. 1 This example for surface micromachining is taken from the microengine developed by Garcia and Sniegowski (1995) and discussed in the section on multilevel micromechanisms. Schematic cross-sections through essential elements of the gear and joints taken at three stages of device completion.

The basic process with a single layer of mechanical polysilicon has been used to fabricate a myriad of devices. The obvious extension of the process is to multiple levels of mechanical polysilicon layers with intervening layers of sacrificial films. However, this extension is not without cost, and the advantages to be gained must be carefully weighed against the development outlay. Earlier work by Fan et al. (1988) illustrated that mechanical elements such as fixed-axle pin joints, self-constraining pin joints, and constrained sliders can be made, and require two layers of polysilicon. This work clearly indicated that the fabrication of movable, connected, mechanical elements is feasible with surface micromachining. However, complex, interactive mechanical devices require yet a third level of mechanical polysilicon to construct. This is easily seen by the following Figs. 2a-c.
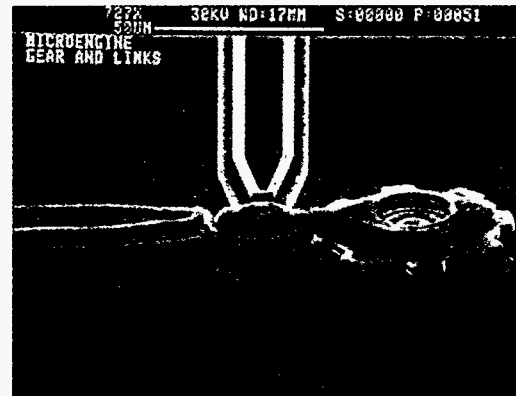
Although not clearly illustrated in Fig. 2, there is an additional polysilicon layer included in these processes. This polysilicon layer does not form mechanical elements, rather, it provides voltage reference planes and electrical interconnects. This film is not considered in the reference to single, double, and triple level processes.
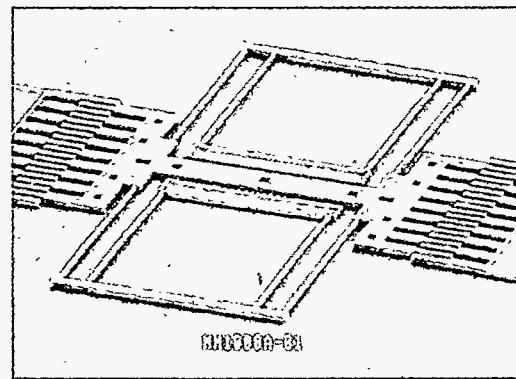
(a)
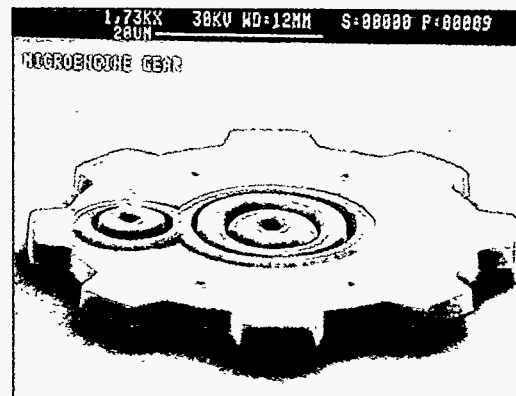
(b)

(c)

FIG. 2. a) Simple, yet very useful structures, particularly for sensor applications, can be fabricated using a single level of mechanical polysilicon. b) A double-level process produces movable mechanical elements. However, connection to these structures is limited. Here a gear with a central hub attached to the substrate and a free-spinning pin along its radius is shown. However, connection to the radial pin is not possible without a third layer of polysilicon. c) A triple level process allows the fabrication of complex, interconnected, interactive mechanisms with actuators. That is, the gear in Fig. 2b is now connected to a linkage element and can be actuated through that element.

Typically, structures constructed with one level of polysilicon are only capable of restricted movement because they are attached to the substrate by elastic members. Although the degree of mechanical complexity possible with a single level process is limited, it can nevertheless produce very useful and commercially viable devices, particularly in sensor applications. One such example is Analog Device's surface-micromachined accelerometer (Kuehnel and Sherman, 1994) which is similar to the simple comb drive pictured in Fig. 2a. Extension to a double-level process (Fig. 2b) begins to allow considerably greater mechanical design flexibility, particularly with regard to rotating elements. As seen in Fig. 2b, a free-spinning gear attached to the substrate with a free-spinning pin at some radius from its center can be produced. However, a third level of polysilicon is needed to couple energy to and from this gear. Fig. 2c illustrates this ability to interconnect elements with absolute, hard linkages made possible through the use of three levels. Note also that any or all of the mechanical layers can be made electrically conductive, thus providing additional layers for electrical interconnect or electrodes. In addition, the multiple layers can effectively thicken the structures. This stiffens the structures to out-of-plane motions, often cited as a inadequacy of polysilicon surface micromachining. The full utility of the three-level process is best illustrated with the example of the geared microengine presented in the section on multi-level micromechanisms.

PLANARIZATION BY CHEMICAL MECHANICAL POLISHING (CMP)

The batch-fabrication of integrated gear-link assemblies by surface-micromachining techniques presents a fundamental difficulty. Vertical topography is introduced by the repetitive deposition and etching of multiple films. The etches create film steps which normally are retained through the remainder of the process. This topography can produce mechanical interference between moving parts, and complicates subsequent process steps. The mechanical interference arises when the interconnecting link must pass over the gear edge, or the concentric retaining hub of the gear, as the mechanism moves through one complete rotational cycle. An example of this interference can be seen in Fig. 2c and close-up in Fig. 3a where the upper link runs over the edge of the gear causing an overhang feature. This feature is due to the conformal deposition of the polysilicon film. Link/gear interference can be alleviated by the microengine design, or by planarization of the surfaces before subsequent deposition of additional films.

In addition to the above design issue, two significant process difficulties arise from severe topography. The first results from the use of highly anisotropic plasma etch processes for the definition of the polysilicon layers. The anisotropy is necessary to obtain the desired vertical sidewalls of the polysilicon structures. However, the very anisotropy of the etch also prevents the etch from removing the polysilicon layer from along the edge of a step. This produces long slivers of polysilicon, often referred to as stringers, along these edges. The stringers can also produce mechanical interference or even electrical shorts. Secondly, photolithographic definition of subsequent layers becomes problematic over severe topography. Photoresist, the photosensitive polymeric coating used to transfer the design into the physical films, becomes difficult to apply, expose, and develop, leading to loss of resolution and definition.
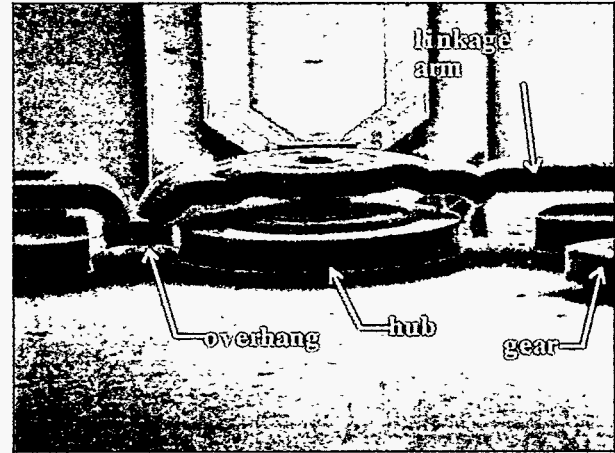
(a)
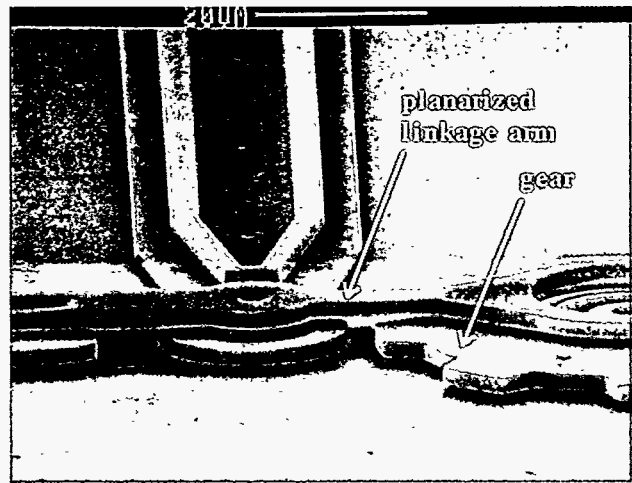
(b)

Fig. 3 The SEM Fig. 3a illustrates the artifacts generated by the conformal nature of the polysilicon depositions over prior topology (indicated by arrows), while Fig. 3b illustrates the same microengine joint feature fabricated with planarization by CMP before the final polysilicon deposition. The overhang artifacts are no longer present.

CMP Applied to Multi-level Surface Micromachining

The recent addition of chemical-mechanical polishing (CMP) planarization to the three-level technology is a major process enhancement from both the process and design perspectives (Nasby et al., 1996). CMP, best known for its global planarization use in sub-micron circuit technology (Patrick, et al., 1991), was first used in the MEMS field to improve the optical quality of polysilicon surface-micromachined mirror devices by smoothing the polysilicon (Yasseen et al., 1995). CMP planarization in MEMS was first reported by Sniegowski (1995). The benefits of CMP for surface-micromachining are four-fold. It eliminates the link/gear interference problem, as illustrated in Fig. 3. It eliminates the artifact of anisotropic etching of conformal polysilicon films over edges, i.e. stringers, since there are no edges on a planar surface. Thirdly, the extension to additional levels of polysilicon becomes

practical since the topography and associated photolithographic problems are eliminated. Finally, CMP enables an innovative approach to the monolithic integration of electronics and surface micromachining which is described below.

CMP Applied to Monolithic Integration

The task of monolithically integrating micromechanics with circuitry is formidable due to conflicts between process conditions used to fabricate optimum circuitry and optimum micromechanics. Combining the two on one chip normally requires compromise. Micromechanical structures typically require long, high-temperature anneals to ensure that the stress in the structural materials of the micromechanical structures has completely relaxed, although research such as that of Biebl et al., 1995 continues to lower the required thermal budget for stress reduction in polysilicon. On the other side, 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. In the CMOS-first approach, the standard aluminum metal used in CMOS is replaced with tungsten. Since tungsten is a refractory metal, it withstands the high-temperature processing, but a number of yield and reliability issues remain unsolved concerning the adhesion of the tungsten layer and the unwanted formation of tungsten silicides. Despite such issues, Yun et al. (1992), for example, have successfully fabricated integrated devices with functioning control electronics.

Alternatively, a unique micromechanics-first approach has been developed (Smith et al., 1995). 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 CMP, and sealed with a nitride membrane. The wafer with the embedded micromechanical devices is then processed using conventional CMOS processing with aluminum metallization. Additional steps are added at the end of the CMOS process in order to expose and release the embedded micromechanical devices. A cross-section of this technology is shown in Fig. 4.
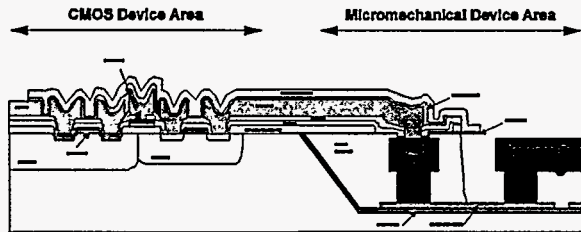

FIG. 4. A schematic cross-section of the embedded micromechanics approach to CMOS/MEMS integration.

Fully functional single-level polysilicon devices have been fabricated in this technology. The three-level polysilicon process has also been recessed and planarized, but not yet combined with circuitry. The significance of this approach is its modularity. The micromechanics and accompanying process can be viewed as separate from the subsequent circuit fabrication process. This allows greater flexibility in how the micromechanics are processed without affecting the circuit process. Likewise, the circuit process sees initially what appears to be a planar, virgin wafer.

Integration is not necessarily required for every micromechanical device application. However, in many cases integration can enhance the functionality of micromechanical devices. For example, integration of control and communication electronics with sensors and actuators reduces overall system size and provides 'smart' processing and communication. Also, increased sensitivity can be accomplished for certain classes of sensor mechanisms by providing on-chip signal-processing electronics. Finally, for large-volume production, the per-unit-function cost may be reduced.

MULTI-LEVEL MICROMECHANISMS

The primary devices to benefit from multi-level processing are micromechanical actuators. Therefore, even though many sensors can be designed and fabricated in the technology, we will concentrate on an actuator, the microengine, for illustration. Unfortunately, micromechanical actuators have not seen the wide-spread industrial use that micromechanical sensors have achieved. Several stumbling blocks to their widespread application have been low force/torque levels, difficulty in coupling tools to engines, and susceptibility to surface effects such as stiction, friction, and wear. The three-level polysilicon micromachining process has aided in producing higher-force actuators and the ability to couple tools to microengines and produce useful work. The surface issues are the subject of the ensuing section.
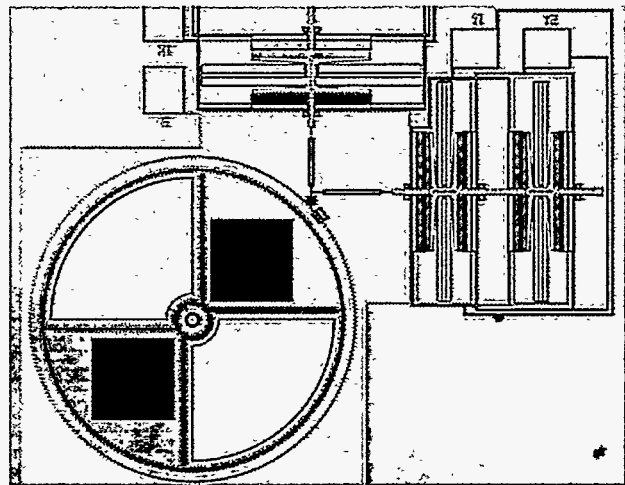

FIG. 5. SEM micrograph overview of the microengine configured to drive a 1600-μm-diameter optical shutter gear. The two linear drives are seen as the two orthogonal electrostatic comb drives in the upper right-hand corner of the micrograph. They are connected by linkages, shown close-up in Figure 3, to the drive gear which is coupled to the driven element by gear teeth.

The microengine presented here in order to illustrate the application of a multi-level polysilicon process is discussed in more detail in Sniegowski et al., (1996). Further details of the basic microengine design are given in the earlier work of Garcia and Sniegowski (1995).
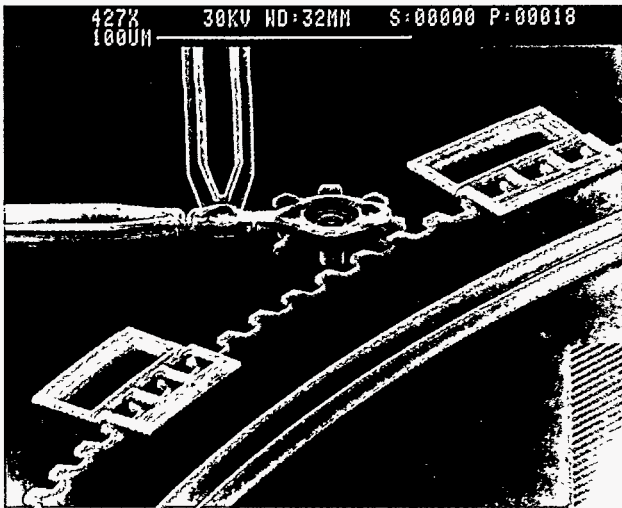
FIG. 6. SEM micrograph of the microengine drive gear coupled to a 1600-µm-diameter optical shutter gear. This gear element is 30 times the diameter of the microengine drive gear. Also present in this photo are a set of retainers used to maintain vertical alignment of the sets of gear teeth, which are only 2.45 µm thick.

FIG. 7. FIB cross-section of a pin-joint which connects the two orthogonal links from the linear drives. The image is of the completed pin-joint with all the layers, including the sacrificial oxide layers still intact.

As a quick review, the principle of operation for the microengine is well described by analogy to two orthogonal pistons connected to a crank shaft, i.e. two linear drive elements connected to a rotary element to produce rotational output. Referring to Fig. 5, the linear drive elements, which are electrostatic comb drives (Tang et al., 1989), are connected by linkages to the rotary drive gear. This

drive gear is then coupled directly to the large gear through the gear teeth. The close-up in Fig. 6 more clearly illustrates the linkages from the linear drives connected to the drive gear.

Figure 7 shows a cross-section of pin joints fabricated in the polysilicon surface micromachining technology. The joint shown has been cross-sectioned by Focused Ion Beam (FIB) milling and SEM imaging. The joint corresponds to the joint between the two orthogonal links from the linear drives and was taken at the fabrication step just prior to removal of all sacrificial films to produce the free-standing mechanical elements.

Having successfully designed, fabricated, and operated the microengine driving a load gear, we considered a gear-speed-reduction unit, i.e. a transmission. To construct the unit required design of dual-level compound gears. This was accomplished by full utilization of the three levels of mechanical polysilicon in the basic process. A dual-level gear-speed-reduction unit that drives a rack back and forth is shown in Fig. 8.
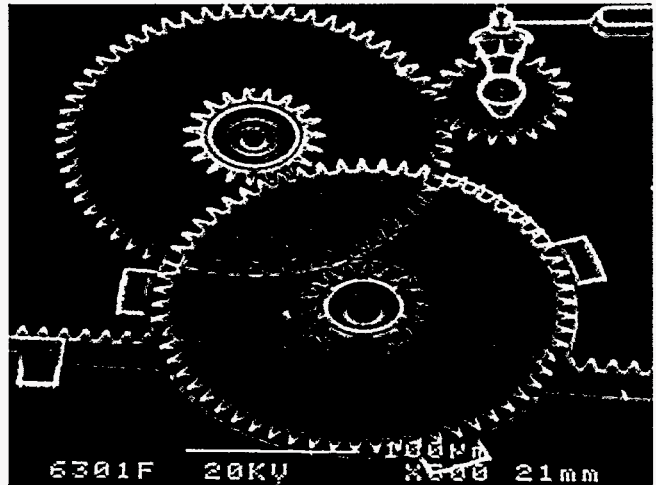

FIG. 8 is an SEM of the completed gear-speed-reduction unit and linear rack. The linear speed of the rack is approximately one tenth that of the linear tooth velocity of the drive gear. The rack has been successfully used to drive a folding mirror, for example.

This assembly utilizes a microengine with a 19 tooth pinion to drive two compound gears that have teeth fabricated in level 2 and level 3 polysilicon. The hubs for all the gears are formed from level 1 and level 2 polysilicon. Each compound gear has a center gear that is about 1/3 the diameter of its outer unit. If we take the gears in order of transmission starting with the drive (pinion) gear, the tooth numbers are 19, 57, 19, 61, and 17 respectively. Thus, the linear speed of the rack driven by the speed-reduction unit is 1/10.77 of what it would be if driven directly by the pinion gear. The lower (level 2 polysilicon) components can be seen in Fig. 9. The large flat areas under the final gear are to provide a planar surface for fabrication of the large level 3 gear. The appearance of gear teeth openings in the large top gear in Fig. 8 are artifacts that compensate for possible mechanical interference caused by the conformal nature of the film depositions in the non-planarized process. Such design constraints were discussed in the previous section. The use of chemical-mechanical polishing for planarization removes such design constraints.

Bi-directional drive of the rack by the reduction unit has been demonstrated. In addition, removal of the rack from the structure allows continuous high-speed operation of the speed-reduction unit.

More significant mechanical loads are coupled to similar microengine driven gear-speed-reduction assemblies and have also been driven successfully.

Further utilization of all three levels of mechanical polysilicon was made by including a bi-level set of fingers and bi-level support springs on the electrostatic comb drives used to power the rotary drive gear (see Fig. 10). The net result is analogous to overlaying two comb drives which effectively increases the net output of the linear drives. However, using bi-level springs separated by a two micrometer thick sacrificial oxide essentially triples the effective out-of-plane thickness of the springs. Since the z-direction stiffness is proportional to the thickness cubed, the threefold increase corresponds to approximately a twenty-fold increase in out-of-plane stiffness. This produces a more robust structure that is less susceptible to stiction problems associated with the springs as well as the shuttle. In addition, a more aggressive layout and design has reduced this comb drive's footprint to 2/3 that of its predecessor.

The dynamical operation of systems actuated by the microengine is governed by the complex relationship between forces, masses, and the physically constrained geometry associated with its moving elements. Relevant forces include the electrostatic forces originating from the applied comb-drive voltages, restoring forces due to the comb support springs, viscous-damping forces, frictional forces between rubbing surfaces, and inertial forces associated with the linear motion of the comb drives and rotational motion of the gears. Though square-wave or sine-wave drive signals can be used to demonstrate functionality and achieve limited operation of the engine, they result in excessive and fluctuating frictional and inertial forces. Such forces can lead to premature failure, and do not result in well-controlled motion of loads being driven by the engine. Specifically, constant angular speed cannot be achieved without the application of specialized drive signals. In addition, rapid acceleration of inertial loads with minimum stress is not possible without properly engineered drive signals.

To enable controlled operation while minimizing parasitic forces, Miller et al. (1996a) have developed and successfully applied a dynamical model of the engine/load system. The results are achieved by analytically solving Newton's equations of motion. The model relates the applied voltages, physical device parameters (e.g. force constants, masses and geometry), frictional forces and load torques, and the time-dependent angular position of the drive gear. Application of the model permits the direct experimental determination of the electrostatic, damping, and spring force constants from functioning engines. The resulting value of Young's modulus is $E \sim 170 \times 10^9$ N/m^2. The measured electrostatic force constant is typically within ten percent of that theoretically expected for the comb drives.

Once the force constants are experimentally determined, the dynamical model is used to extract the load forces acting on the drive gear from measurement of the time-dependent angular position of the drive gear, given the applied drive voltages. From a series of different loading conditions, the coefficient of friction between the gear and hub is experimentally measured to be approximately 0.5. The maximum speed of an engine thus far achieved is 300,000 rpm. The speed record was obtained with no load attached to the drive gear. The endurance record achieved thus far for a single engine is $3.2(10^9)$ revolutions while operating at a speed of 146,000 rpm. The engine also accrued 66,300 start/stop cycles during the $3.2(10^9)$ revolutions.
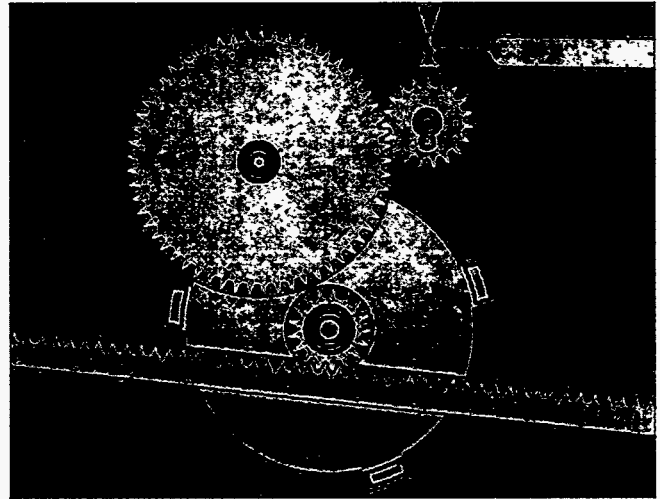

FIG. 9. Shown in this micrograph are the three lower level gears and rack in the gear-speed-reduction unit.
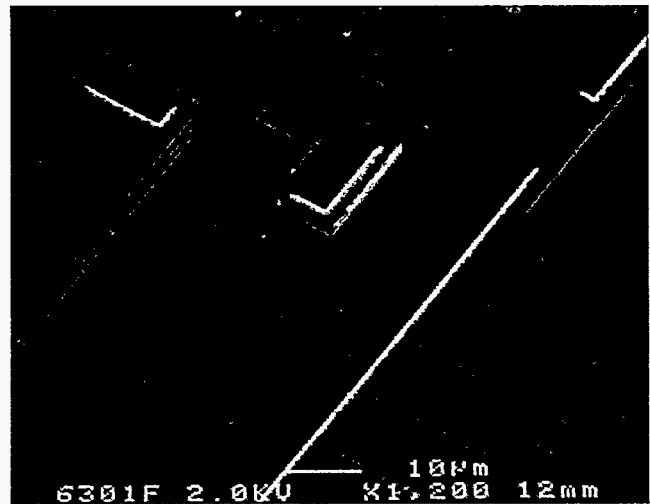

FIG. 10. Utilization of multiple levels of mechanical polysilicon is seen in this SEM image of bi-level comb drive fingers and support springs. Each layer is approximately 2 µm in thickness. In this case, the bi-level nature of the structures arises from the sacrificial oxide layer that was present between polysilicon layers during fabrication.

THE CRITICAL ISSUES: STICTION, FRICTION, AND WEAR

Although several issues continue to be important to polysilicon surface-micromachining, e.g., the measurement of thin film materials properties, and thin film residual stress measurement and control, they are not hindering the use of the devices to the extent of the surface related phenomena. Experience with the microengine, geared micromechanisms, and sensor structures has convinced us that many devices can be adequately designed and fabricated with the desired mechanical attributes, but that the device surface phenomena of stiction, friction, and wear present the greatest impediment to common usage. Obviously, in the last section we illustrated a structure referred to as a speed-reduction unit

rather than a torque-multiplication unit. That was done precisely because we do not yet adequately understand the frictional losses in these structures. Using the basic microengine with the analysis of Miller et al. (1996b), we are attempting to extract information on the frictional behavior. Under many conditions the devices display 'macroscopic' friction behavior having a coefficient of approximately 0.5.

Post-release chemical treatments and wafer handling greatly affect the possible outcome of the devices (see for example, Guckel, et al. 1989, Alley et al., 1992, Legtenberg, et al., 1994). The problem is so extensive and evasive that a significant portion of the MEMS literature deals with it. In particular, the phenomena of stiction affects both sensors and actuators during the final release stage of fabrication and during use of the devices (in-use stiction). The issues of friction and wear primarily applies to actuators. As a MEMS fabrication technology, polysilicon surface-micromachined structures tend to be the most sensitive to stiction. This is chiefly due to their surface-to-volume ratio and the scaling behavior of various surface effects to these small dimensions, e.g. liquid-vapor surface tension. In particular, liquid-vapor surface tension forces (typically water - air menisci) which occur during the drying of parts after the final liquid HF release etch are responsible for bringing surfaces into contact. Recall that the final removal of the sacrificial films to produce free-standing structures is done with a liquid hydrofluoric acid etch. It is during the subsequent drying process that the effects of stiction affect the structures. A dominant force being the surface tension of the liquid-vapor surfaces which form as the device dries. The references by Alley et al., (1992), Legtenberg, et al., (1994) provide a review of stiction forces. Typical surface micromachine device fabrication also exacerbates the problem. Nominally, they are constructed close to the supporting substrate ($\leq 3\mu m$) and are comprised of relatively thin films ($\leq 4\mu m$). Thus their dimensions enhance the attractive forces which induce them to adhere and often do not provide sufficient mechanical stiffness to prevent it.

Stiction

Since stiction is pervasive for many MEMS devices, we start with a brief overview of how the problem was and is dealt with. For greater detail, Dyck et al. (1996) provides a review and discussion of the stiction literature. It was recognized early that the surfaces of micromechanical devices when brought into intimate or even close proximity to other parts of the structure or the substrate would adhere, although the details of the adhesion mechanism were unknown. A relatively successful early approach to eliminate stiction involves eliminating or circumventing the forces which produce the intimate contact of surfaces susceptible to adhering to themselves or to the substrate.

Examples of commonly used methods of this approach include freeze-sublimation (Guckel, et al. 1989), supercritical carbon dioxide drying (Mulhern, et al. 1993), polymer supports (Mastrangelo and Saloka, 1993), photoresist support (Orpana and Korhonen, 1991), or fusible links (Fedder and Howe, 1989). Freeze-sublimation and supercritical carbon dioxide drying eliminate the liquid-vapor surfaces during drying so that the structures are not forced into contact or close proximity. The other methods physically support the structures during the drying process so that contact does not occur. The physical supports are then removed in a dry plasma process in the case of photoresist or polymer supports, or severed by current pulses in the case of fusible links. Unfortunately, in most cases the free-standing structures still retain highly adhesive surfaces. For elastically suspended

structures in which surfaces never contact during use, this may not be a problem. However, in practice sensor elements can be subjected to forces during use or storage which cause contact and therefore possibly adhesion (in-use stiction). A surface modification such as a thin silicon-nitride film can reduce this occurrence (Guckel et al., 1989).

Unfortunately, actuators such as the microengine will always have some parts of the structures in contact with each other, e.g., in the joints. Therefore, the chemically active surfaces must be modified. It has been known for some time that physically roughening the surfaces make them less susceptible to adhesion (Guckel et al., 1989). Yee et al. (1995) used this approach to reduce sticking of microstructures. However, it is often undesirable, for mechanical or optical reasons, to have rough surfaces.

Surface Modification - Hydrophobic Surfaces

Possibly the most promising research for surface modification is the chemical treatment of the released device surfaces to increase their hydrophobicity. This raises the H_2O contact angle above 90 degrees creating a repulsive force between adjacent surfaces that prevents them from contacting each other as they are drying. Such behavior has been reported for surface treatment with self assembled monolayers (SAMs) (Alley, et al., 1992) and ammonium fluoride (Houston, et al., 1995).

Deng et al. (1995) reports favorable results applying SAMs to their micromotors. Very recently, Houston et al. (1996) reports extremely good results in decreasing stiction effects during post-fabrication release and long term passivation of the surfaces with SAM application. This direction of research appears very promising for application to the microengine in addition to general application to polysilicon surface-micromachined structures.

Friction and Wear

As expected, friction and wear greatly impact the performance of the microengine and associated structures. The issue of friction is closely tied to the stiction problem. Once stiction is overcome, the devices behave quite well exhibiting 'normal' coefficients of friction. Our experience to date with various surface treatments, including SAMs, indicates this as a promising path. Although we do not have conclusive data regarding the reduction of friction and wear with the application of SAMs, the indication of the preliminary test data clearly dictates a thorough examination. The question remains whether the SAMs will readily wear off.

Wear will probably be the last issue to be attended to directly. However, with the strong relationship between these phenomena and a little serendipity, solutions to stiction and friction may also provide a solution for long lifetime. Clearly though, the order of solution must be first, to move structures (solve stiction), second, to move them smoothly and easily (solve friction), and thirdly, with the first two solved, to move them for a long time (solve wear).

Along these lines, several researchers have looked at possible methods of reducing both friction and wear.

Liquid Lubricants. With the application of liquid lubricants, the formation of menisci with the accompanying surface tension forces will disallow a liquid lubricant to be localized to the moving joint or slide areas only. Liquid lubrication will require total immersion of the devices. If total immersion is acceptable in the application of the device, the research of Deng et al. (1993) with their micromotors and our own microengine results with a lubricant such as silicone oil predicts very acceptable results. A

specific result is that operation in a liquid tends to make the device behavior more repeatable and uniform. Unfortunately, the speed of operation in these fluids is greatly reduced relative to operation in air due to viscous drag. When considering that typical lifecycles are in the millions to billions of cycles for operation in air, to repeat this number of cycles at the reduced speed implies a nearly infinite lifetime. On the other hand, other failure mechanisms such as slow drifting of contaminants in the fluid due to electrostatic attractive forces exist.

Solid Lubricants. The use of materials of dissimilar hardness in bushing applications for rotating devices is common practice in the macro-world. This concept was reasonably extrapolated into the micro-world. Therefore, films such as diamond-like-carbon, silicon carbide, and silicon nitride for example have been proposed and tried in microstructures. Constraints on the film include compatibility with the process and process tool set and whether it can be deposited on the proper surfaces. Silicon nitride is a film which readily qualifies on both issues. The friction-reduction benefit was demonstrated with some of the early micromotors (Fan et al., 1989) and friction test structures (Lim, et al., 1990). Several researchers since that time have seen similar results. This area continues to show potential in dealing with friction and wear, and new films are continually being explored.

Self Assembled Monolayers as Lubricants. The micromotor work of Deng et al. (1995) suggests that both friction and wear can be decreased with the application of SAMs. However, the type of micromotor they investigated operates in a mode with rolling friction as opposed to the sliding friction that occurs in actuators such as the microengine. Whether the effects of SAMs are beneficial to friction and wear needs to be determined for the class of devices with sliding friction such as the microengine.

Fluorocarbon coatings. The recent work of Man et al. (1996) regarding the deposition of conformal fluorocarbon (Teflon-like) films onto released structures suggests that these films may also eliminate stiction and reduce wear. Their results indicate a tough, very stable film which conformally coats the released structures.

SUMMARY

Polysilicon surface micromachining is a process technology that Sandia has exploited for a variety of micromechanical sensors and actuators. The general process available provides three levels of polysilicon for mechanical constructions ranging from simple doubly clamped beams for sensing to intricate interconnected linkages and joints for actuation. The basic process has been enhanced by the inclusion of chemical-mechanical polishing to allow easier mechanical design and processing while offering the extension to additional levels of polysilicon and a novel approach to the monolithic integration of CMOS microelectronics with surface micromechanics

The issues of stiction, friction, and wear are not yet fully resolved. They must be addressed adequately before we will be able to use the microengine as a driver in applications which have requirements from reliable start-up after long dormancy to continuous high-speed operation. Fortunately, surface treatments with self-assembled monolayers, possibly followed by deposition of thin Teflon-like films, appear to be very promising approaches. Recent successes demonstrated by several researchers in these areas

suggests these surface treatments to be broadly applicable to polysilicon surface micromachining, including multi-level devices such as the microengine.

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