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**TRIBOLOGICAL ISSUES OF POLYSILICON SURFACE-
MICROMACHINING**

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1. Abstract

Polysilicon surface-micromachining is a Micro-Electro-Mechanical Systems (MEMS) manufacturing technology where the infrastructure for manufacturing silicon integrated circuits is used to fabricate micro-miniature mechanical devices. This presentation describes a multi-level mechanical polysilicon surface-micromachining technology and includes a discussion of the issues which affect device manufacture and performance. The multi-level technology was developed and is employed primarily to fabricate microactuated mechanisms. The intricate and complex motion offered by these devices is naturally accompanied by various forms of friction and wear in addition to the classical stiction phenomena associated with micromechanical device fabrication and usage.

2. Introduction

Fabrication by polysilicon surface micromachining can provide both sensors and actuators. However, microactuators with associated micromechanisms typically present the most severe cases of tribological surface contact and thus the greatest challenge to tribologists. Microsensors, on the other hand, typically fail due to adhesive effects which occur after contact between various surfaces of the device and the supporting substrate. These adhesive effects, often referred to as stiction by micromachinists, is a very significant subset to the general subject of tribology in these devices. Mastrangelo recently [1] presented an in-depth discussion of adhesion related failures and discussed several practical methods for the elimination of the forces which induce contact between surfaces and for the elimination of the intersolid adhesion mechanisms. Briefly summarized, adhesion related failures for structures which are elastically supported above the substrate can be circumvented by design using normalized elastic member dimension bounds. This prevents the collapse or pinning of the various elements of a device structure by assuring their mechanical stiffness exceeds the contact forces. If this is not

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possible, as with the design of highly compliant structures needed for sensitive accelerometers, Mastrangelo reviewed the use of a wide variety of process, surface treatment, and physical schemes. Further, Henck [2] provides another recent and excellent summary of Texas Instruments Incorporated extensive work on adhesion related failure and lubrication of their Digital Micromirror Device™ (DMD™). This is probably the most comprehensive work to date that addresses the tribological issues related to a micromechanical device. Another case, where no elastic supports are present to separate potentially contacting surfaces, is common to many microactuated mechanisms. In this case, surface-to-surface contacts are inevitable.

In this paper, we present a general description of Sandia's polysilicon surface-micromachining technology, the level of device complexity accomplished, and the technology's tribological issues. Examples of geared actuators coupled to other geared micromechanisms are used to illustrate the tribology requirements of this technology. The latter portion of this paper presents several tribology related challenges yet to be solved. The detailed nature of the device surfaces and their processing history affects the mechanical and tribological behavior of surface-micromachined devices often in a more dramatic and peculiar fashion than analogous macro-scale devices. An overview of the types of tribological surfaces, as determined by the fabrication process, are described. These surfaces usually exhibit different surface topography which may have significant impact at these dimensions. For example, the surface topography can be generated by dry plasma etch, or by the surface of a deposited film. Another challenge is the quantitative investigation into the details of the surface condition and topography is hindered by the "micro" size of the features.

3. Polysilicon Surface-Micromachining Technology

Polysilicon surface-micromachining has a number of very desirable manufacturing attributes resulting from its close relation to the infrastructure used in the manufacture of microelectronic integrated circuits (ICs). However, the technology does not readily lend itself to producing devices with tribologically preferred materials nor to producing devices readily amenable to classical tribological treatments such as the use of liquid lubricants or hydrodynamic bearings. New solutions to tribological issues must be developed for surface-micromachining to reach its fullest potential.

3.1. WHY USE POLYSILICON SURFACE MICROMACHINING

The key advantages to polysilicon surface-micromachining are that the process is a batch-fabrication technology which does not require piece-part assembly, and that it utilizes the IC infrastructure which is capable of large-scale, low-cost (per unit) production. Polysilicon micromachining, relative to other micromachining technologies, utilizes the greatest cross-section of IC tools and process technology. The IC manufacturing infrastructure has the potential to produce tremendous quantities of fully-assembled, ready-to-operate, micromechanical devices at very low per-unit costs as

long as the device fabrication remains within the constraints of the technology. The aspect of pre-assembled parts is very significant. These parts are in the fully-assembled state after the final release step of the process and are ready to be operated. Without this integral method of assembly and batch-fabrication, intricate techniques for mass assembly would need to be developed.

Secondly, considering the physical size of the devices, there are not many means of accurately defining such small geometries. The more conventional means of machining, although capable of holding tolerances to micron dimensions, are not capable of defining complex geometries with such dimensions. Thus, producing a gear with dimensional control to a few microns with a computer controlled milling machine is readily accomplished. But, this same tool cannot produce a gear of 100 micron diameter with 10 micron gear teeth. It is the photolithographic tools developed for the definition of the IC electronic devices that readily allow the definition of such microscopic gears. A quick review of the MEMS literature clearly illustrates that nearly all forms of micromachining, from bulk micromachining to LIGA, utilize the IC photolithographic tool set to define their devices.

Because of its small size, polysilicon surface-micromachining technology presents unique tribology challenges. Their IC-like fabrication constrains the choice of construction materials. Polysilicon, although a very reasonable mechanical material, does not have optimal tribological properties. In general, the technology presents like-material contacts and polysilicon is poor with regards to wear load. Consideration of more desirable tribological material in the form of non-standard IC films pose contamination issues for IC foundries or are often incompatible with standards processes. Finally, the use of thin film technology and small geometries make the devices highly susceptible to surface forces. Fortunately, multiple film technology enables extensive innovation regarding design solutions to tribology related limitations. For example, mechanical stiffening of structures significantly reduces their susceptibility to external forces. In addition, multiple layers are allowing us to produce much higher force actuators which greatly improve device reliability in regards to overcoming stiction. Recent results hold promise that we will be able to move out of the regime where stiction is very significant.

3.2. THE FABRICATION TECHNOLOGY

Surface micromachining manufactures micromechanical devices utilizing the planar fabrication techniques common to the microelectronic circuit fabrication industry. Constructing devices in this technology consists of adding and selectively defining layers of thin films onto a flat silicon substrate. The complexity of the technology is defined by the number of polysilicon layers. Therefore, a N-level technology refers to N layers of polysilicon (poly) films deposited including both non-structural and structural films. Most often, the first layer is a thin ($\leq 3000\text{\AA}$) electrically conductive film of polysilicon which is used for electrical interconnect and for defining voltage reference planes. Subsequent polysilicon layers, typically $0.5\text{--}4.0\text{ }\mu\text{m}$ thick, provide the structural layers from which the mechanical elements are constructed. Interspersed

between the polysilicon layers are layers of a sacrificial film, usually silicon dioxide, which provides the spacing between the polysilicon layers and acts as a mold to hold the layers of polysilicon during the fabrication process. Therefore, a N-level polysilicon surface-micromachining technology has, as its basic process module, the repetitive cycle of deposition and definition of two primary films, a sacrificial silicon dioxide film and a structural polycrystalline silicon film. The deposition, photolithography, and etch processes are based on those commonly used for integrated circuit (IC) fabrication, but modified for thicker, mechanically-optimized films. For example, the polysilicon and silicon dioxide films are typically deposited by low-pressure chemical vapor deposition (LPCVD), while reactive ion etch techniques are used for film definition. A 4-level process in essence repeats this base sequence 4 times.

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 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 are batch-fabricated in a ready-to-operate form on a single six-inch silicon substrate.

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 [3] which is similar to the simple comb drive pictured in Figure 1a. Extension to a double-level process (Figure 1b) begins to allow considerably greater mechanical design flexibility, particularly with regard to rotating elements. As seen in Figure 1b, 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. Figure 1c 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.

To illustrate actual fabrication steps in relation to producing functional elements, Figure 2a shows the gear in Figure 1b in cross-section. Figure 2b schematically indicates the gear, the hub which anchors the gear to the substrate while allowing rotation, and a pin joint at the outer radius for connection to a link to drive the gear. This represents the functional elements of the structure, while Figure 2c illustrates the same cross-section but with respect to the order of polysilicon film depositions used to form the structure.

(a)

(b)

(c)

Figure 1. a) Simple, yet very useful structures, particularly for sensor applications, can be fabricated using a two-level process with one layer of interconnect poly and one layer of mechanical polysilicon. b) A three-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 fourth layer of polysilicon. c) A four-level process allows the fabrication of complex, interconnected, interactive mechanisms with actuators. That is, the gear in Figure 1b is now connected to a linkage element and can be actuated through that element.

From the perspective of physical embodiment, this technology allows the construction of quite complex machinery (see Figures 3-7). However, micromechanical machinery have not yet seen the wide-spread industrial use that micromechanical sensors have achieved. Several issues historically limiting their widespread application have been low force/torque levels, difficulty in coupling tools to engines (for technologies with few mechanical layers), and susceptibility to surface effects such as stiction, friction, and wear. The four-level polysilicon micromachining process developed at Sandia has aided in producing higher-force actuators and the ability to couple tools to microengines and produce useful work. The surface issues remain as an active area of research.

(a)

(b)

(c)

Figure 2. The top image a) is of the cross-section through a microgear generated by focused ion beam (FIB) milling. The schematic b) below it indicates parts of the gear by functional design, while c) illustrates the order of the film depositions during fabrication.

Figure 3. The microengine converts orthogonal movement from the X and Y comb drives into rotational movement of the output gear.

3.3. DEVICE EXAMPLES

The micromachine [4,5] has evolved as one of the primary actuation mechanisms for MEMS at Sandia. The device consists of two orthogonal linear drivers and a pair of linkages coupled to an output gear. This is essentially a 2-D version of pistons, connecting rods, and a crankshaft. Our standard form of linear drives are electrostatically controlled comb drives (Figure 3).

The microengine, in turn, can be coupled to a gear cluster capable of increasing the available torque (Figure 4). An example of a system powered by the microengine and transmission is the fold-up mirror used to redirect an optical signal (Figure 5).

Figure 4. SEM of the gear cluster unit and linear rack. The gear ration is approximately 10:1 in this case. 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.

Figure 5. SEM of the gear cluster unit and linear rack being used to fold up a pop-up micromirror.

As a final example, Figure 6 illustrates the combination of several functions which form the basic elements of a combined micro-lock and micro-optical system. The entire operation of unlocking the lock and switching the position of the optical shutter have been demonstrated and can be accomplished in under 100 milliseconds. Several of the images illustrate surfaces which have sliding contact (Figures 6a,b,c for example) or normal contact (Figure 6g). Therefore, the issue of adhesion and friction are critical to the assembly's operation.

Figure 6. Several images are taken of a micromechanical assembly which combines the functions of a lock and optical shutter. Figure 6f is the overview of the entire pin-in-maze lock, center bottom, and the shutter wheel, upper-left. The other images are close-up of the various elements, such as a latch and hook (images d,h,g).

3.4. STATUS OF THE TECHNOLOGY

The current level of device complexity may be best illustrated by figure 7 where a gear box with a three million-to-one gear ratio has been fabricated in the 4-level process. The device is being used to demonstrate gear cluster complexity and to study the coupling efficiency of geared elements. It has already been demonstrated that gear clusters such as this can multiply torque to a level where buckling pop-up mirrors (Figure 7) from the substrate plane is reliably accomplished. Results indicate that force multiplication places very high loads on elements and may be potentially capable of fracturing the material. This capability is currently being quantified. This may have application to materials testing in addition to a broad range of other applications.

Figure 7. A perspective view of a 3,000,000:1 gear cluster illustrates the complexity available with a 4-level poly process.

Analogous to the IC world, the addition of independent layers permits greater design freedom and complexity. Thus, extension to a 5-level technology is being pursued [6]. From the design perspective, the utility of a 5-level polysilicon/oxide stack is schematically depicted in Figure 8. This technology allows a designer to consider stacking complex, moving structures on top of movable structures. This, in essence, allows micromechanisms to be conveyed about the substrate surface to interact with each other or with the environment. From the manufacturing perspective, this adds another level of challenge for the tribologist.

Figure 8. Schematic depiction of the utility of a 5-level technology. Structures capable of movement and manipulation can be placed on plates which can convey them to other locations on a substrate.

4. The Tribological Issues

This section presents examples of the contacting/sliding surfaces encountered with polysilicon surface-micromachined devices. A major aspect of this technology is that the devices, upon release, are fully-assembled. Thus, parts cannot be lubricated and then assembled. Even if separated, it would be extremely difficult to handle the individual elements for coating.

The support springs for the microengine and travel limiters in Figure 9 illustrate a set of "open" contacting surfaces which could be treated with a line-of-sight application method. However, the application of a lubricant will not, in most cases, be line-of-sight due to the fully-assembled nature of the technology. Rather, the lubricant will need to penetrate under surfaces and into relatively small apertures ranging from as small as 0.1 micron to a couple of microns. For example, the cross-section of the gear in Figure 2 showing the gear teeth, the hub, and pin joint is much more typically of surfaces which need lubrication. The teeth are a vertical surface and are line-of-sight.

However, the contacting surfaces of the pin joint and hub present covered surfaces and apertures on the order of 0.5 micron. The effective coverage of coatings, such as the self-assembled monolayers, on these surfaces is under investigation.

Figure 9. SEM close-up of multi-level support springs and a travel limiter which significantly increase the robustness and reliability.

Figure 10. SEM close-up of a hinge used to connect and allow the fold-up of the mirrors show in Figure 5. Note that all three layers of mechanical poly are easily discernible.

The joint shown in Figure 10 allows the folding of the large plates which comprise the micromirrors in Figure 5. Several aspects of the fabrication technology are illustrated by the figure. The 2-D nature of the design with the third dimension arising from the stacking of the films is apparent. The joint does not have the cylindrical appearance of a typical journal bearing. This results from the journal being defined in the thin film by a plasma etch which produces vertical walls relative to the surface of the film. True 3-D machining is beyond the capability of the technology at this time. The surfaces can be inspected and illustrate two types of topography. One is the surface produced by the deposition of the film itself. These are the top and bottom surfaces of the films. This surface typically has RMS roughness on the order of tens of nanometers. The other surface encountered are the sidewalls of the films defined by the plasma etch technique. They typically have a characteristic striation pattern with the striations running vertically. Measurement of the sidewall roughness is much more difficult. The impact of these surface roughness on friction and wear is an active area of research. Surface roughness is known to affect stiction and is discussed below.

5. The Critical Issues: Stiction, Friction, and Wear

Although several material 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 functions, but that stiction, friction, and wear present the greatest impediment to common usage. Using the basic microengine with the analysis of Miller et al [7], we are extracting information on the frictional behavior. Under many conditions the devices display 'macroscopic' friction behavior with a friction coefficient of approximately 0.5.

5.1. STICTION (ADHESION-RELATED FAILURE)

Post-release chemical treatments and wafer handling greatly affect the possible outcome of the devices. 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 [8], Legtenberg, et al [9] provide a review of stiction forces. Typical surface micromachine device fabrication also exacerbates the problem. Nominally, they are constructed close to the supporting substrate ($\leq 3\mu\text{m}$) and are comprised of relatively thin films ($\leq 4\mu\text{m}$). Thus their dimensions enhance the attractive forces which induce them to adhere and often do not provide sufficient mechanical stiffness to prevent it.

By their very nature, actuators such as the microengine will always have some parts of the structures in contact with each other, e.g., in the joints. Therefore, chemical modification of active surfaces is desirable to reduce adhesion. It has been known for some time that physically roughening the surfaces make them less susceptible to adhesion [10]. Yee et al [11] used this approach to reduce sticking of microstructures. However, it is often undesirable, for mechanical or optical reasons, to have rough surfaces. Maboudian and Howe [12], Mastrangelo [1], and Henck [2] recently contributed reviews which detail the methods currently available for either circumventing or eliminating stiction or adhesion-related failure.

5.2. FRICTION AND WEAR

Beyond adhesion-related failure, friction and wear obviously 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.

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).

5.2.1 *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 [13] with their micromotors and our own microengine [14] 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.

5.2.2 *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 [15] and friction test structures [16]. 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.

5.2.3 *Self Assembled Monolayers as Lubricants*

The micromotor work of Deng et al [17] and our microengine research 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. The question whether the SAMs will readily wear off has been partially answered by Henck [2]. His results are consistent with our observations of the behavior of the microengine. There is initial reduction in the coefficient of friction (cof), followed by slightly longer lifetime than untreated surfaces but the SAMs appear to wear off and the device begins to behave as an untreated device. Senft and Dugger [18] have reported initial results on the study of SAMs using surface micromachined tribological test devices.

5.2.4 *Fluorocarbon coatings*

The work of Man et al [19] 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. We have also initiated an effort to investigate these films, but using commercially available plasma tools and standard IC process gases (e.g. CHF_3) [20]. Initial results are promising and research is continuing. The cof is reduced to less than 0.1, comparable to bulk TeflonTM, however these films also indicate wear-off behavior. Therefore, lifetime has not been extended dramatically.

6. The Future

Polysilicon surface micromachining is a very promising technology that Sandia has exploited for a variety of micromechanical sensors and actuators. The general process available provides four 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

Complex devices have been shown to operate with full functionality and to operate at speeds up to several hundred thousand revolutions per minute while accumulating several billions of cycles. While major improvements have been made, the issues of stiction, friction, and wear are not yet fully resolved. They must be further addressed before we will be able to use the microengine as a reliable driver in applications which have requirements from 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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