5-LEVEL POLYSILICON SURFACE MICROMACHINE TECHNOLOGY: APPLICATION TO COMPLEX MECHANICAL SYSTEMS

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ABSTRACT

We recently reported on the development of a 5-level polysilicon surface micromachine fabrication process consisting of four levels of mechanical poly plus an electrical interconnect layer [1,2]. We are now reporting on the first components designed for and fabricated in this process. These are demonstration systems, which definitively show that five levels of polysilicon provide greater performance, reliability, and significantly increased functionality. This new technology makes it possible to realize levels of system complexity that have so far only existed on paper, while simultaneously adding to the robustness of many of the individual subassemblies.

INTRODUCTION

Although MEMS is the acronym for MicroElectroMechanical Systems, the "systems" aspect is not often exhibited since limitations imposed by established technologies restrict design complexity and the interactions that can occur between components. A new 5-level polysilicon surface micromachine fabrication process now provides a base for designing sophisticated mechanical systems-on-a-chip. To demonstrate this, we combined totally redesigned versions of many previously demonstrated concepts: electrostatic actuators, microengines, transmissions, rack and pinion assemblies, self-positioning mirrors, and a pin-in-maze discriminator [3,4,5] into a single interconnected system. Also demonstrated for the first time are the fabrication of gears on moveable plates, shaft and bushing interconnect linkages, embedded hold-down pins in a linear rack, and guides with release mechanisms that keep mating sets of gears in proper alignment until engagement occurs. This is believed to be the most complex, fully actuated, surface micromachined mechanical system ever fabricated. The drawing set contains hundreds of thousands of entities on 17 drawing layers. These are combined to generate 14 photolithographic masks that are used during the 240-step fabrication sequence. Functionality of this system was demonstrated with components from the first production run confirming that performance, reliability, and complexity could all be simultaneously improved by this 5-level technology.

5-LEVEL POLYSILICON STACK

Figure 1 depicts the 5-level polysilicon / silicon dioxide stack that is the basis for this technology. Referred to as SUM-MiT-V (Sandia Ultra-planar Multi-level Mems Technology V) [6], four mechanical levels of polysilicon are fabricated above a

Figure 1. Shaded regions represent the 5 levels of polysilicon, and the clear spaces between them represent layers of sacrificial oxide. This stack is built on a 6-inch single crystal silicon wafer with a dielectric foundation of 0.63 μm of oxide and 0.80 μm of nitride.

thin poly0 electrical interconnect layer. Two microns of sacrificial oxide is typically sandwiched between each polysilicon level. The oxide between poly1 and poly2, however, is only 0.5 μm thick. This thin deposition defines the clearance in gear hubs and hinges. In areas surrounding the hubs and hinges, it is often etched away so that the 1.0- μm thick poly1 and the 1.5- μm thick poly2 form a single rigid composite layer. Poly3 and poly4 are 2.25- μm thick films that are deposited on chemically mechanically polished (CMP) layers of oxide [7]. This CMP planarization alleviates several photolithographic and film etch issues and frees the designer from constraints that would otherwise be imposed by the underlying topography.

GOAL OF WORK

Driving the development of this work was the goal of designing a research prototype that demonstrates the feasibility of building complex microelectromechanical systems for enhanced safety of weapons.

Requirements:

- System is to be fabricated using multi-level surface micromachining technology.
- Its function is to provide for directing an optical data signal to a target electronic assembly only after the correct electrical sequence is fed to a micromechanical discriminator (lock).
- System is to be fabricated in the disabled state.
- A predefined 24-bit code will be used to enable the system.

- The discriminator will be a single attempt device, with any incorrect code sequence permanently disabling the system.
- Optical access for the data signal is to be through holes cut from and through the backside of the fabrication substrate. Openings will be 400-500 microns in diameter to accommodate a Vertical Cavity Surface Emitting Laser (VCSEL) or a small fiber optic cable.
- Discriminator shall incorporate low power actuators that permit the enabling code to be optically entered.

Envisioned was a system of two positionable mirrors fabricated in close proximity to each other so that light entering through a hole in the substrate would strike one mirror, be deflected to the other mirror, and then back down through the second substrate opening and on to the target element (figure 2). These mirrors would be fabricated flat against the substrate and driven to the correct position by electrostatically controlled microengines [8]. To prevent operation prior to receiving the unlock sequence, a mechanism comprised of an incomplete gear train, which is to couple the power from microengines to the linear racks that drive the mirrors, would be employed. To enable the system, a set of power coupling gears must be inserted to

Figure 2. Dual-mirror-redirect safety concept. Mirrors are fabricated flat over these openings and cannot be driven to this operating position until the proper keys are inserted into their drive mechanisms.

complete the drive train. The gears that form these power coupling links would be mounted on moveable structures attached to linear pin-in-maze plates “cut” with the binary code. Upon completion of the correct code sequence, these gears would become fully engaged. The CAD drawing for the actual implementation of this system is shown in figure 3. Note that two of these assemblies are required for full beam routing.

Figure 3. Enhanced versions of several previously demonstrated MEMS devices were redesigned in the 5-level technology so that they could be integrated into a single unified system. A total of 39 gears ranging in size from 72 to 288 μm in diameter are employed along with 5 electrostatic actuators, 2 rack and pinion assemblies, a linear maze track with 3 embedded hold down/guide pins, 1 set of guide rails, 2 autoreleasing gear alignment mechanisms, a pop-up mirror with 12 hinges and self-shadowing etch release hole covers, and a rotary anti reverse mechanism. Eleven electrical connections are required for system operation.

PERFORMANCE AND RELIABILITY

As system complexity increases, the yield and reliability of individual components must be very high in order to have appreciable yield of the entire system. This is especially true of actuator assemblies, which must provide enough force to reliably drive significant mechanical loads. To first order, using one

Figure 4. All four mechanical layers of polysilicon are utilized to increase electrostatic actuator performance. In this region, the first two are laminated together to form a more rigid base layer.

Figure 5. Similar layering of the support springs generates a structure that is approximately 100 times stiffer than first generation devices in the "z" axis.

level, the amount of force obtainable from an electrostatic actuator is proportional to its size [9]. Additional fabrication levels allow the structure to be built up vertically instead of laterally, significantly increasing the amount of force available per unit area. All of the mechanical levels available in the 5-level technology are layered together to form the actuators shown in figure 4. Even more important than the increased force performance, however, is the dramatically increased "z" axis stiffness that results from stacked levels in the actuator support springs (figure 5). The cubic relationship between thickness and stiffness makes these structures approximately 100 times as stiff as their first generation counterparts in the "z" direction. This increases robustness and helps tremendously in the final release process where the surface tension of the etchant acts to pull the moveable portion of the comb drive assembly down to the underlying substrate and leaves it adhered. These drives are far more reliable and generate several times the force of the original devices.

This multi-level technology also promotes reliability by permitting the exploration of alternative linkages between the linear electrostatic actuators and drive gears that comprise each microengine. The shaft and bushing linkage shown in figure 6 pivots like earlier pin joints [8]. It does not, however, have the large inverted rivet head structure associated with pin joints that could come in contact with the underlying substrate and reduce reliability due to stiction. This type of linkage also generates less off axis torque on the comb drive than commonly used elastic links, thus reducing the possibility of lateral clamping between the electrostatic actuator fingers [4].

Drive force from the new high-output microengine is further increased through the use of the cascaded gear reduction unit shown in figure 7. Each unit provides a 12:1 gear reduction ratio with a corresponding increase in torque. Six of the units have been coupled together to provide a 3 million to 1 gear reduction assembly that has demonstrated the ability to shear gear teeth. The actual safety system uses three of the 12:1 gear reduction units to create a 1728:1 transmission that drives the linear rack containing the maze. This produces ample force to overcome friction and stiction effects [2,10] and provides 138 nanometer positional resolution of the rack per microengine revolution.

Figure 6. Close-up of low stiction linkage assembly that interconnects one of the microengine linkage arms with its electrostatic actuator.

Figure 7. Each cascaded gear reduction assembly increases drive torque by an order of magnitude.

Figure 8. This early rotary pin-in-maze discriminator was fabricated in a 4-level polysilicon process.

ENHANCEMENTS AND NEW FUNCTIONALITY

We initially demonstrated that pin-in-maze discriminators could successfully be fabricated in a surface micromachine technology with the 3-decision point rotary device shown in figure 8 [5]. As the maze wheel rotates, the control arm must move a pin that rides inside the maze radially back and forth so that the pin never takes a dead end path. Once a dead-end path is taken, the lock is permanently disabled due to an anti-reverse mechanism that prevents retries. If all the correct paths are taken, the wheel will rotate until the pin comes to the very end of the maze, and at this point the device is considered to be unlocked [11]. Although useful for demonstration purposes, this design was not directly expandable to the desired 24-bit functionality, since the maze pattern actually cuts all the way through the maze wheel. The longer the maze pattern, the more the outside portion of the maze is severed from the main wheel. Thus a maze with 24 decision points would not be structurally sound.

The rotary maze was fabricated in a 4-level polysilicon technology, while an additional level of material is needed to support larger mazes. Figure 9 illustrates how this was accomplished with the 5-level process for the 24-bit linear pin-in-maze

configuration. Essentially everything was moved up one level and a solid flat plate was defined under the maze to support each side of the structure. The additional level of structural material also allowed pins to be embedded within the structure of the rack to confine its movement both vertically and laterally. A representative cross section of the moveable portion of the maze track assembly is indicated with the light gray fill at the bottom of figure 9.

On one end of this rack is a plate with two power coupling gears that will be inserted into and complete the mirror drive train upon completion of the unlock sequence. These two sets of gears are pictured in figure 10. As the gears engage, their rotational alignment guides simultaneously disengage through release mechanisms fabricated in the top 2 levels of polysilicon. After this occurs (figure 11), the mirror control engine can be activated to drive the mirror into the correct operating position. Figure 12 shows the two opposing mirrors required for complete system implementation. The mirror on the right has been enabled and driven to the desired operating position, while the mirror on the left is in its fabricated state. The spring-like structures on the mirror sides apply pressure on the gears and hinges to facilitate precise positioning.

Figure 9. Scanning electron micrograph and CAD layout of a section of the maze track assembly and control arm.

Figure 10. As the linear pin-in-maze discriminator is operated, power coupling gears on the maze track plate (right) move towards the uncoupled gears in the mirror drive train (left) and complete mechanical coupling. Rotational alignment guides automatically release when gears engage, and a spring clip snaps in place to prevent plate disengagement.

CONCLUSIONS

With a 2-level polysilicon technology, it is possible to make simple actuators; with 3 levels, gears with hubs; and with 4 levels, linkages that attach to the gears to provide continuous 360° rotation. The 5-level technology presented here now allows complex moveable components to be fabricated on translatable stages. This permits significant interactions to occur between

various subassemblies, thereby allowing the mechanical “systems” aspect of MEMS to be much more realizable.

In addition, full utilization of these levels, even in structures that can be defined in a single mechanical layer, has been shown to have significant benefits on performance and reliability. Although data on a statistically significant number of components is not presently available, almost all of the first run devices were found to be functional. Hundreds of assemblies will

Figure 11. After the successful negotiation of the maze, the coupling gears complete the mirror drive train. Note that the alignment guides are now pulled away from the gears.

Figure 12. With its gear train completed, the mirror on the right has been driven to its correct operating position. Operation of the second mirror will establish the optical data path.

be subjected to extensive testing once baselining of this technology is complete.

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