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Surface micromachined counter-meshing gears discrimination device

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ABSTRACT

This paper discusses the design, fabrication and testing of a surface micromachined Counter-Meshing Gears (CMG) discrimination device which functions as a mechanically coded lock. A 24 bit code is input to unlock the device. Once unlocked, the device provides a path for an energy or information signal to pass through the device. The device is designed to immediately lock up if any portion of the 24 bit code is incorrect. The motivation for the development of this device is based on occurrences referred to as High Consequence Events. A High Consequence Event is an event where an inadvertent operation of a system could result in the catastrophic loss of life, property, or damage to the environment.

Keywords: stronglinks, counter-meshing gears, discriminators, coded devices, lock-out mechanisms

1. INTRODUCTION

Safety devices have been designed at Sandia National Laboratories for more than forty years. Stronglinks are electromechanical safety devices which serve as lock-out mechanisms. Stronglinks receive information in the form of coded drive signals and, given the correct code, provide a path for an energy or information signal to pass through the device. They are designed to survive or fail in a safe state in abnormal environments or inadvertent accidents. Traditionally, stronglinks are fabricated using conventional machining practices. Today efforts are underway to investigate the practicality of using micromachining techniques to produce stronglinks for retrofit applications. Both deep x-ray lithography (commonly referred to as LIGA) and surface micromachining (SMM) technologies are being explored. This paper presents the work accomplished on a SMM counter-meshing gears (CMG) device, a device which is used as a discriminator mechanism in a stronglink.

Micromachined devices are of interest for a number of reasons, they are smaller in size and weight, less expensive since hundreds of identical devices can be produced simultaneously, and inherently more rugged in extreme vibration and shock environments. Also, with SMM technology, no piece part assembly is needed since devices are batch fabricated in the assembled state. The SMM CMG device was fabricated using the Sandia Ultra-Planar Multi-Level MEMS Technology (SUMMIT) process. The discussion below is divided into five sections. The first section discusses the stronglinks and discriminators, the next two sections discuss the design, fabrication and test results of the device. The last two sections discuss future work and summarize work on this project.

2. STRONGLINKS AND CMG DISCRIMINATORS

Stronglinks consist of four primary elements: drivers, discriminator mechanisms, couplers, and monitors. Drivers are linear or rotary actuators which are used to drive discriminator mechanisms. Discriminators are mechanical mechanisms that function as a coded locking device. Discriminator mechanisms are designed to irrevocably fail and render the device inoperable if the wrong drive signals are sent to the device. Typically, a 24 bit code is used to unlock discriminators. Couplers provide a path for energy transmission; this path can be optical, magnetic, electrical or mechanical. If the correct code is received by the stronglink, the drivers unlock the discriminator mechanism and drive the couplers into proper alignment position to pass an energy or information signal through the device. Monitors are used to interrogate the state of the device.

A counter-meshing gears discriminator mechanism consists of two separately driven gears [1] and two counter-rotation pawls. Each gear is driven by a separate actuator in the same rotational direction by a set of drive signals that drives each gear in

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specific increments in a specific sequence relative to each other. Figure 1 illustrates the basic CMG configuration. Each gear is a composite consisting of five layers; three gear layers each separated by a spacer layer (Fig. 2). The five layers are assembled and fastened together so there is no relative motion between the individual layers.

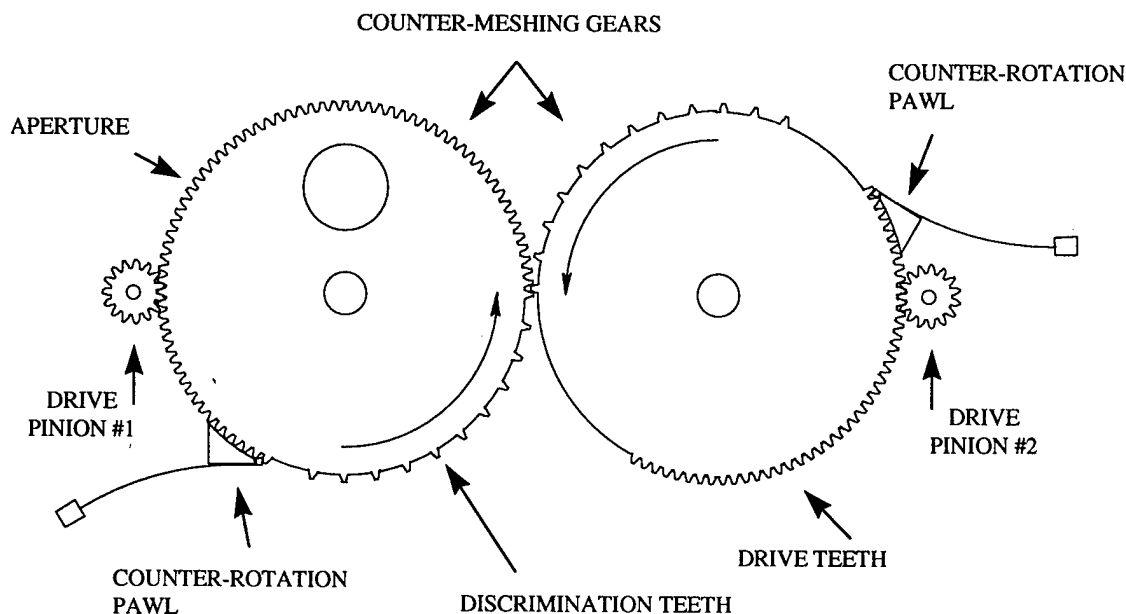


Figure 1. Conceptual drawing of a Counter-Meshing Gears Discriminator Device.

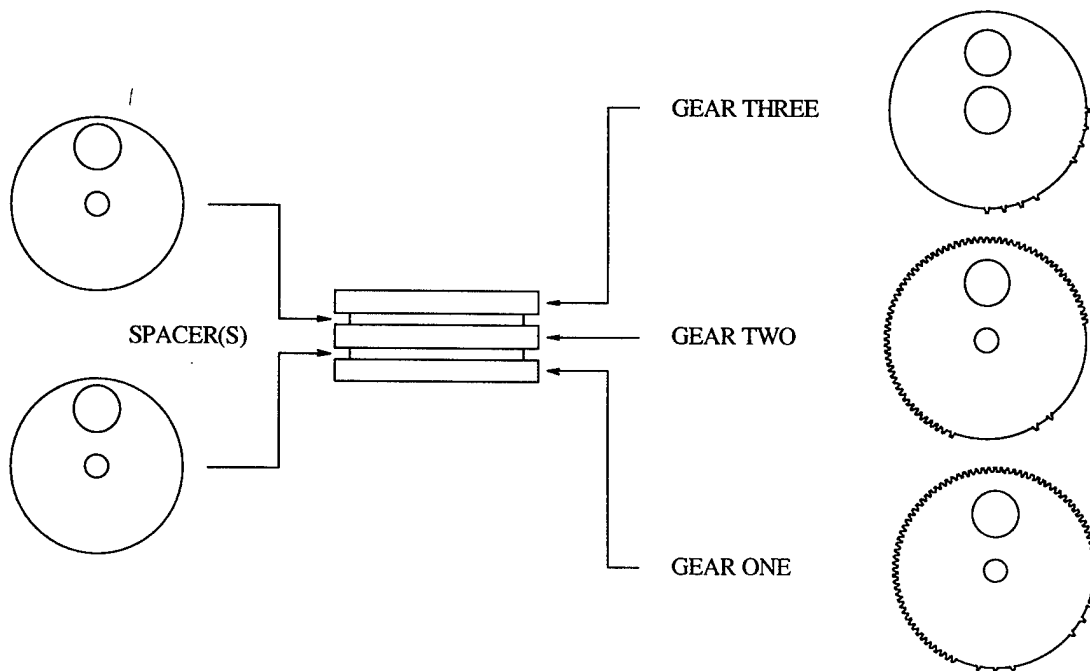


Figure 2. Five-level composite gear

The three gear layers are configured so that a coded pattern is developed by the way the teeth are positioned in the vertical stack. A design rule limits the number of teeth in each vertical stack position to a maximum of two teeth and a minimum of

one tooth. For example, in the first stack position of the composite gear, there might be a tooth on the first gear layer, a tooth on the second gear layer, and no tooth on the third gear layer as shown in Fig. 3. Or there might be one tooth on the second gear layer, one tooth on the third gear layer, and no tooth on the first layer like that shown in Fig. 4. The design rule enables a code to be established in the composite gears so that by indexing the gears in proper sequence, the teeth will pass over or under one another without interference (Fig. 5). If the wrong indexing sequence is used, the teeth on the composite gears interfere which results in a device lock up.

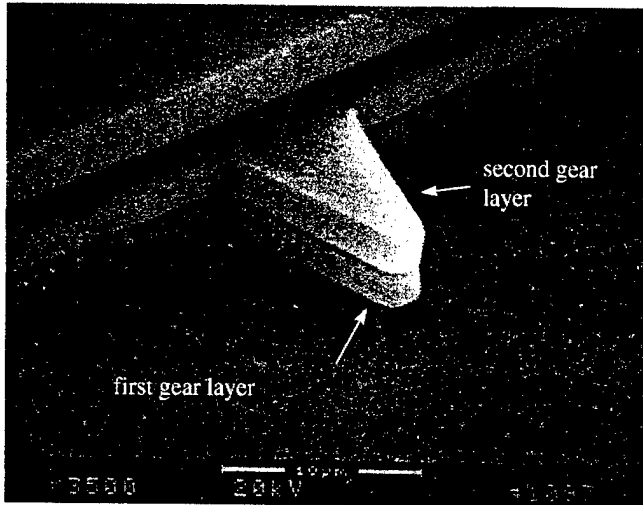


Figure 3. Teeth on the first and second gear layers.

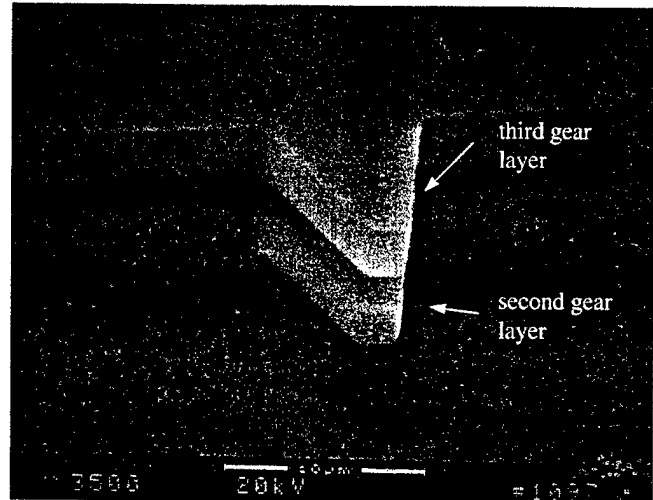


Figure 4. Teeth on the second and third gear layers.

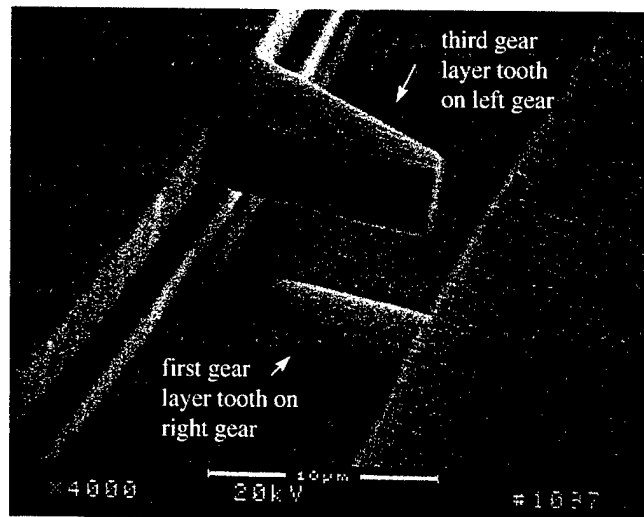


Figure 5. Engagement area between the CMG.

Complete lock-up of the device also requires the use of counter-rotation pawls to prevent rotation in the opposite direction. These devices limit the rotation of the gears to one direction as shown in Fig. 6. There are several designs utilized for counter-rotation pawls; the one shown in Figure 6 is a cantilever beam anchored at one end and fabricated with a gear tooth on the free end. Positioned next to the beam is a fixed stop. As the gear rotates in the counter-clockwise direction, the beam deflects and tooth ratchets through the teeth on the gear. The gear cannot be driven in the clockwise direction since the tooth on the end of the beam is driven into the fixed stop and wedged into position. This action prohibits the gear from turning in that direction.

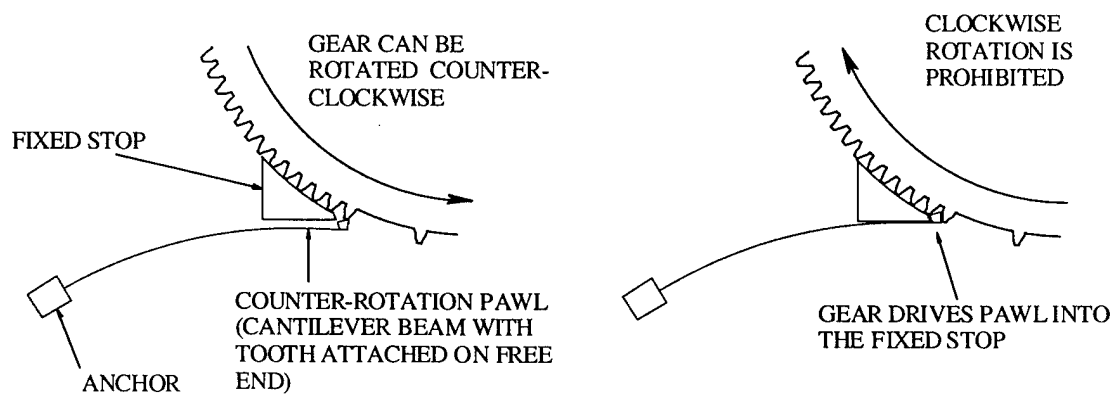


Figure 6. Conceptual drawing of a counter-rotation pawl.

If the wrong drive signals are sent to the actuators, the composite gears are indexed into a position where the teeth interfere. At this point, the driven composite gear attempts to drive the other composite gear the opposite direction. Counter-rotation pawls prohibit this rotation and render the device irrevocably locked up. The CMG device is designed to immediately lock-up if any one of the 24 bits that make up the drive signals is incorrect.

3 SMM CMG DESIGN AND FABRICATION

The SMM CMG device shown in Figure 7 is fabricated using Sandia's SUMMiT process. Four separate layers of polysilicon are deposited and used to fabricate the device. The first polysilicon layer is used as an electrical ground plane and the other three layers are used to fabricate the structural elements. For example, the first, second and third gear layers are constructed from the second, third and fourth polysilicon layers, respectively. The device occupies a 4.7 millimeters by 10 millimeters area. The device consists of CMG, two rotary actuators (used to drive the CMG), two counter-rotation pawls, and two linear actuators (used to reset the pawls for testing purposes).

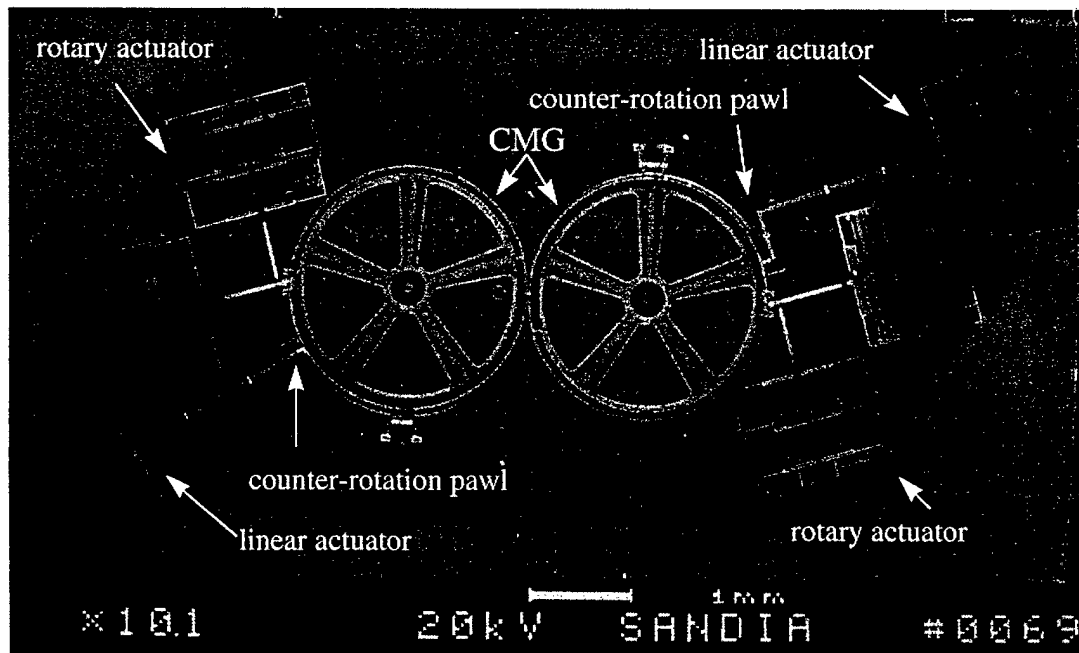


Figure 7. SMM CMG discrimination device.

The CMG are 2 millimeters in diameter and contain two different sets of teeth, drive teeth and discrimination teeth (Fig. 8). The drive teeth are used to rotate the gears and the discrimination teeth are used for the coded pattern. Drive teeth are positioned around roughly half the perimeter of each gear. They are fabricated using two polysilicon layers and are 2.5 micrometers thick. The design for the drive teeth is based on a 450 tooth gear with a 20 degree pressure angle. An involute profile is used for the tooth definition.

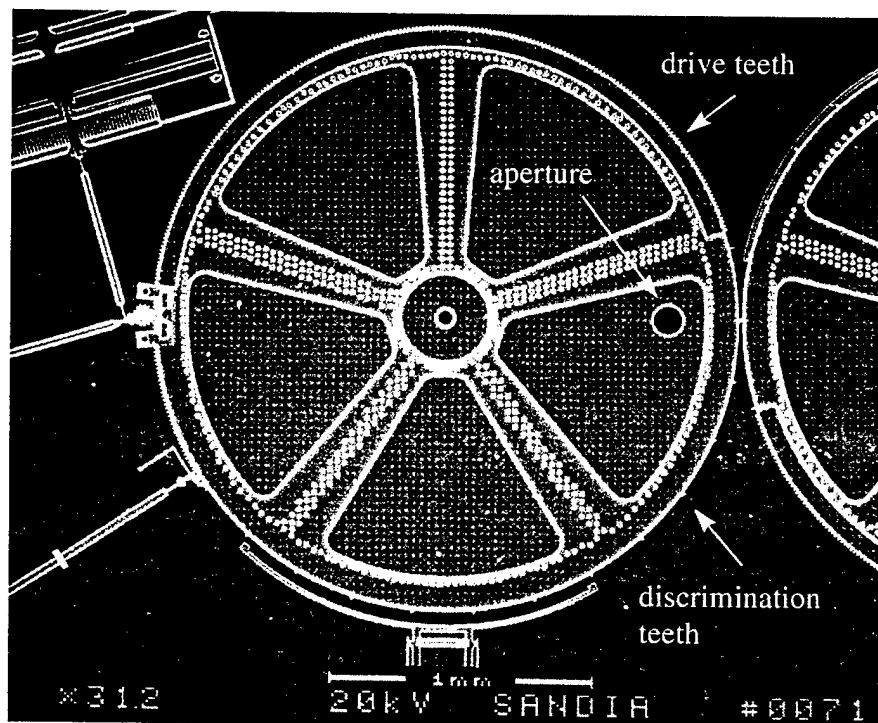


Figure 8. Left counter-meshing gear.

The discrimination teeth are located on three polysilicon layers as previously shown in Figures 3, 4, & 5. A gap is fabricated between each layer to mitigate unwanted interference that might occur if the gears were to tilt in the plane of fabrication during operation. The tooth thickness for the second, third and fourth polysilicon layers are 1, 1.5 and 2 micrometers, respectively. The space between the teeth on the second and third layers is 0.5 micrometers. The space between the teeth on the third and fourth layers is 2 micrometers. The pitch between each composite tooth is 12 degrees.

The mechanical structures are fabricated by standard SMM techniques. Polysilicon and silicon dioxide (SiO_2) layers are deposited, followed by lithography, development, and etching processes which are used to define the structures. Silicon dioxide is used as a sacrificial layer and deposited between polysilicon layers. The sacrificial layer is wet etched during the final release process using a hydrofluoric acid solution which does not affect the polysilicon. As the materials are deposited they conform to the topography of the underlying surface. Conformal deposition posed a problem in defining some of the coded discrimination teeth. For this design, some parts of the code required teeth on the third polysilicon layer in areas where there are no underlying teeth in the second polysilicon layer (Fig. 9). To deposit the third layer in the correct plane a removable shim was designed (Figures 10 & 11). This shim was positioned one micrometer from the dedendum circle of the gear. The shim is designed to act as a support for the third polysilicon layer as it is built up during the chemical vapor deposition (CVD) process. After the device is released, the shim is mechanically moved with a probe into a constraint device which holds it in a neutral position away from the CMG device (Fig. 12).

A chemical mechanical polishing (CMP) process is used to planarize the silicon dioxide layer between the third and fourth polysilicon layers. After the CMP process is completed, the surface is left completely flat and parallel to the wafer substrate. This process mitigates the conformal deposition problems mentioned above. Thus, we encountered no processing problems in fabricating discrimination teeth in the fourth polysilicon layer in areas where discrimination teeth are absent below them (Fig. 5).

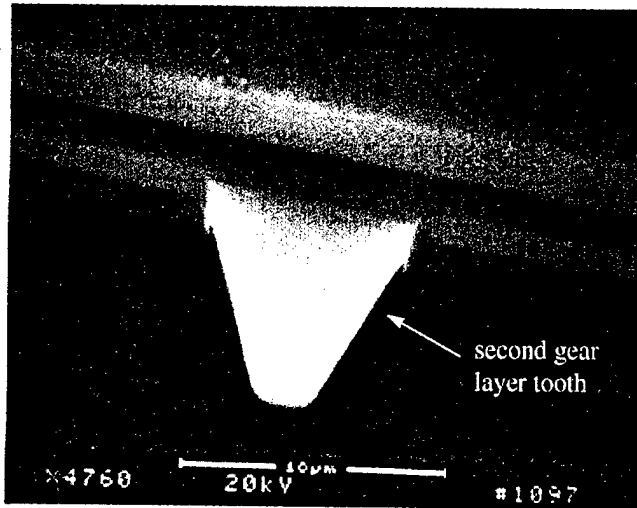


Figure 9. Discrimination tooth fabricated in an area where no tooth is fabricated below.

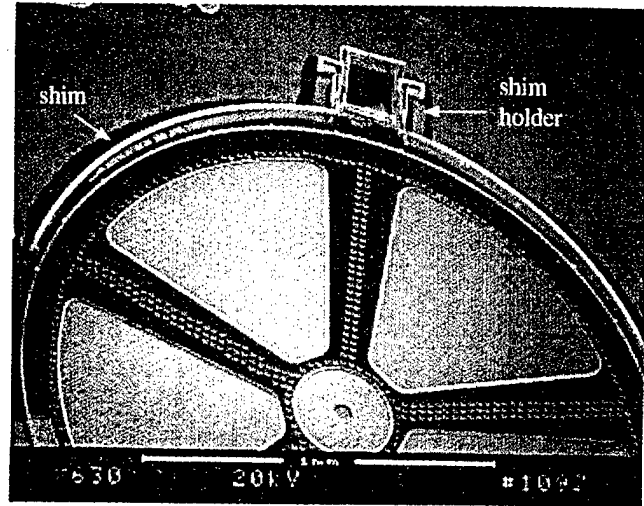


Figure 10. Shim used to fabricate discrimination teeth.

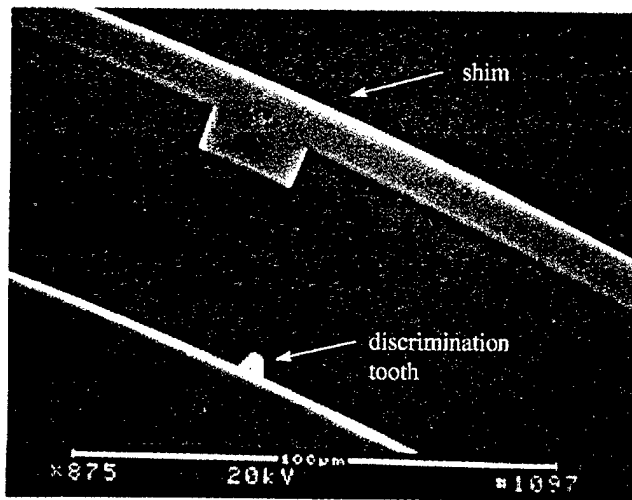


Figure 11. Tooth fabricated above shim.

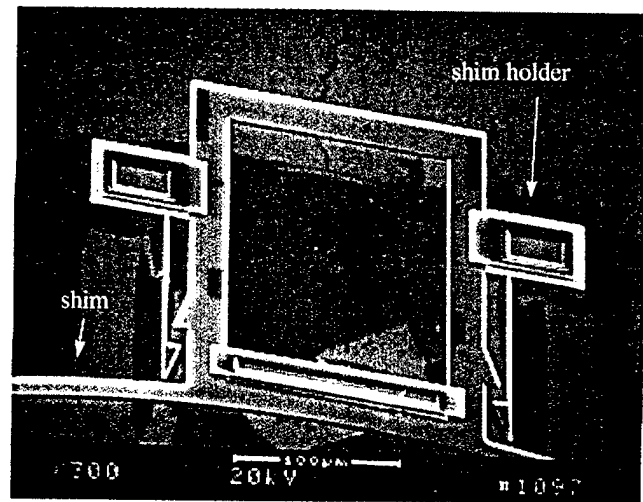


Figure 12. Shim positioned in shim holder.

To fully unlock the discriminator mechanism, each gear must be rotated in a proper indexing sequence through 144 degrees. A 100 micrometer diameter aperture is fabricated in the left gear to represent a stronglink energy coupler. Once the discriminator mechanism is unlocked, rotating the left gear an additional 12 degrees aligns the aperture into the open position. If this device were to be used for a stronglink application, post processing steps would be needed to deposit a metal layer on the gear to reflect optical energy and a wafer back etch process would be needed to provide an optical path through the silicon substrate.

The drivers used to rotate the gears are rotary actuators known as Microengines [2] which can produce greater than 25 pN-m output torque. A second design obstacle encountered pertained to the control of Microengines. The CMG design requires accurate twelve degree indexing of each gear to unlock the discriminator. Presently, a feedback system for these actuators is not yet available; however, work is underway to develop one. To overcome our control problem we took advantage of the inherent tendency of a Microengine to rotate one complete rotation. This is due to the folded-beam spring design which tends to restore the suspended comb structure to its initial position under light loading conditions. In addition, the drive signals can be tailored to achieve full rotation indexing.

To achieve proper indexing of the CMG, pinions 75 micrometers in diameter containing 15 teeth were designed. The CMG drive tooth design is based on a 450 tooth gear. By rotating the pinion one full revolution, twelve degree indexing is attained:

$$\theta = \frac{N_p}{N_g} 360^\circ \quad (1)$$

where N_p is the number of teeth on the pinion, N_g is the number of teeth on the gear, and θ is the index angle. The disadvantage to this approach is it requires the diameters of the CMG to be large which increases the size of the device and drive torque requirements to operate it.

Stronglink discriminator mechanisms are designed to operate one time. Once actuated, the device remains locked in position. This is accomplished by incorporating a stop which prevents the CMG from rotating past the fully actuated position. The counter-rotation pawls prohibit counter rotation hence the device becomes locked in place when fully actuated. A right-angled beam design was used for the counter-rotation pawl design to achieve the correct spring constant (Figure 13). A notch was designed in the tooth at the free end of the beam. This notch catches a support beam affixed to the substrate during an attempt to drive the gear in the clockwise direction. To reset the device, the counter-rotation pawls must be withdrawn and the drive signals sent in the reverse order. Reset mechanisms were added to the CMG design to afford a testing capability. The reset design utilizes a linear comb-drive actuator to drive a linkage mechanism shown in Fig. 14 to completely disengage the pawl.

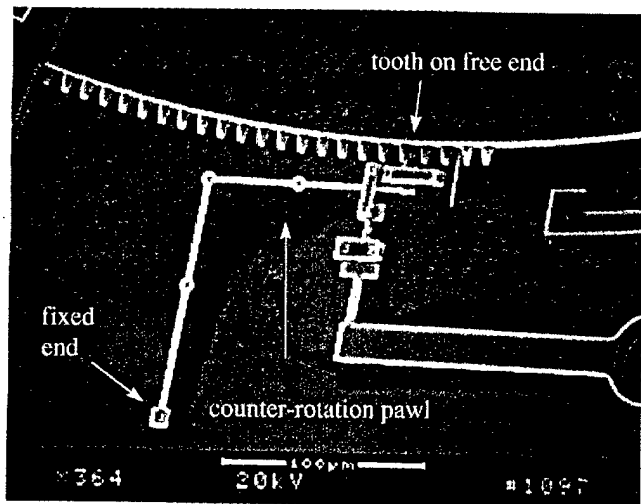


Figure 13. Counter rotation pawl prohibits clockwise gear rotation.

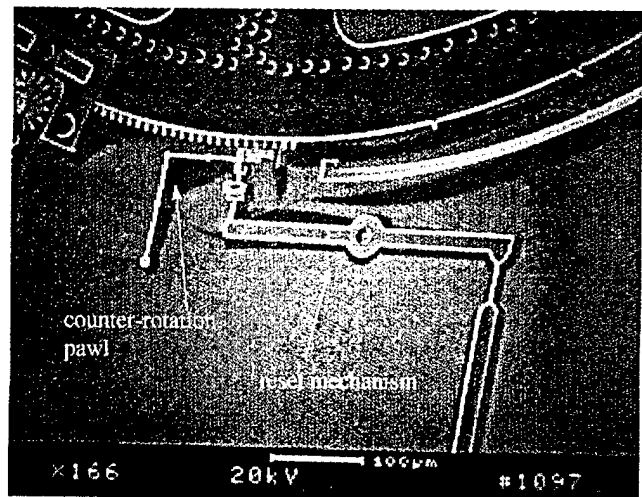


Figure 14. Reset mechanism used to reset the Counter-rotation pawl.

4 RESULTS

After fabrication, the devices were placed on a probe station and visually inspected for defects. The shims used to aide in fabricating the discrimination teeth were repositioned manually into shim holders as shown in Fig. 12. The shim holder locks the shim into a neutral position so that it does not interfere with device operation. Visual inspection of the discrimination teeth verified the shims worked as designed, *i.e.*, the teeth on the third polysilicon layer were fabricated in the correct plane.

A probe card that contains thirteen probes was used to provide electrical connections for testing. Twelve probes are used to supply electrical energy to the two rotary actuators and two linear actuators and one probe is used for an electrical ground. Our test set up includes a PC, LabView® software and analog output card, amplification hardware, and a break out box for electrical connections.

The device was initially tested by manually entering the 24 bit drive signal one bit at time. No problems were encountered indexing the gears. Next we developed a control program which enabled us to adjust the angular velocity of the drive pinions and input the entire 24 bit code automatically. Our results were exceptional. We ran many tests varying the pinion speed from 1 revolution per second to 85 revolutions per second with the CMG device operating as designed. With the pinion speed set at 85 revolutions per second we were able to input the entire 24 bit drive signal and actuate the device in roughly one second. At pinion speeds greater than 85 revolutions per second the device locked up. We believe this is due to limitations in our test setup associated with switching a mechanical relay. We intend to modify our test setup to circumvent this problem. Performance testing will be addressed in the future. To reset the device, the linear reset actuators were energized disengaging the counter-rotation pawls. The CMG were then reset by driving the gears in the reverse direction using the reverse order of the 24 bit code.

Next the code was tested to verify whether or not the discriminator fails if the wrong drive signals are sent. An incorrect code was entered where the teeth on the first mechanical polysilicon layer were tested. The device immediately locked up. The counter-rotation pawls locked the device into position and we were not able to drive either Microengine in forward or reverse directions to unlock the device. Next we reset the device using the reset mechanisms and proceeded to verify that the teeth on the other two polysilicon layers functioned properly. These tests verify the lock-up feature functions as designed.

5 FUTURE WORK

To attain the proper gear indexing, Microengine output gears (pinions) were driven one complete revolution. This approach worked quite well, however, the diameters of the CMG must be large enough to accommodate sufficient drive teeth and discrimination teeth to drive the gear and discriminate the code. For the SMM CMG device described above, the pinions were designed with 15 teeth. Thirteen indexing events are needed for code discrimination and aperture alignment. Therefore, the counter-meshing gear must possess enough drive teeth to rotate the gear through the thirteen indexing events and accommodate the counter-rotation pawls. These factors led to the design of 2 mm diameter CMG.

To reduce the gear diameters without feedback control, two design approaches are under investigation. The first design uses a transmission between the pinions and the CMG to tailor indexing. Full revolution pinion indexing is still employed with an appropriately geared transmission to generate a design specific CMG rotation. With this approach we can reduce the CMG diameters 75 percent to 500 micrometers. There are two disadvantages with this approach, the transmission adds additional loading due to frictional effects and additional die area is needed to accommodate the transmission. Nevertheless, we can reduce the die area needed for the device by 50 percent with this design approach.

The second approach uses full rotation pinion indexing with a pinion having only one tooth. The tooth is designed so that the contact ratio between the pinion and the CMG is one; thus, for every full rotation of the pinion, the CMG indexes one tooth. With this approach we can reduce the CMG diameters to 300 micrometers. We have fabricated CMG designs with this approach and have encountered problems with impacts between the tooth on the pinion and teeth on the gear. If the gear rotates too much or too less collisions between the teeth occur. Currently we are investigating a design to position the CMG correctly with the counter-rotation pawls to mitigate this problem.

Future work will incorporate a different energy coupling mechanism. We plan to integrate a Micro-Flex pop-up mirror [3] with the CMG design. This device will redirect a beam of light traveling parallel to the substrate normal to the substrate. The discriminator will be used to unlock the device and actuate the mirror. The device could be used as a light switch with a mechanical lock [4].

Packaging and environmental testing are also under investigation. Stronglinks must survive or fail in a safe state in abnormal environments such a transportation and storage environments. Thermal tests as well as shock and vibration tests are planned for this device. We also plan to package these devices in commercially available packages and wire bond the electrical connections. We plan to report on these activities in the future as the project matures.

6 SUMMARY

The long range goal for this project is to determine the practicality of fabricating safety devices known as stronglinks using micromachining processes. To accomplish this goal a SMM CMG discriminator has been designed, fabricated and driven.

Discriminators are one of four fundamental elements of a stronglink. The CMG discriminator uses a 24 bit code entered in proper sequence to unlock the device.. The mechanism is such that if any one of the 24 bits in the code is incorrect, the device immediately locks up and is rendered inoperable. Actuation times as-fast-as one second have been measured. Tester limitations have prohibited testing the device at faster speeds. However, we anticipate much faster actuation times once our tester hardware has been modified.. Performance testing verified the device functions as designed. The device locks up when the wrong 24 bit code is used.

Future work for the next generation devices include reducing the overall size of the device. To accomplish this the actuator control schemes must be modified so that the CMG diameters can be reduced. Two design approaches are under investigation: The first utilizes a transmission positioned between the drive pinion and the gears to achieve specific indexing. The second uses a pinion with one tooth to index the CMG in one tooth increments. Packaging and environmental testing is another area that we are beginning to investigate. We plan to address these issues and report our results as the project matures.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

- [1] E. J. Garcia and J. J. Sniegowski, "Surface Micromachined Microengine as the Driver for Micromechanical Gears," Proc. 8th Int. Conf. Solid-State Sensors and Actuators (Transducers '95), Stockholm, Sweden, June 25-29, 1995, vol. 1, pp. 365-368.
- [2] E. J. Garcia and J. J. Sniegowski, "Surface Micromachined Microengine," Sensors and Actuators A (48), pp.203-214 (1995).
- [3] E. J. Garcia, "Micro-Flex Mirror and Instability Actuation Technique," Proc. of Eleventh IEEE International Workshop on Micro Electro Mechanical Systems (MEMS'98), Heidelberg, Germany, January 25-29, 1998.
- [4] J. J. Sniegowski and E. J. Garcia, "Microfabricated Actuators and their Applications to Optics," Proc. SPIE, San Jose, CA, vol.2383, 1995, pp. 46-64.

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