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SURFACE MICROMACHINED COMPONENTS FOR A SAFETY SUBSYSTEM APPLICATION

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ABSTRACT
We have designed and fabricated a system using micromachining technologies that represents the first phase of an effort to develop a miniaturized or micro trajectory safety subsystem. Two Surface Micromachined (SMM) devices have been fabricated. The first is a device, denoted the Shuttle Mechanism, that contains a suspended shuttle that has a unique code imbedded in its surface. The second is a mechanical locking mechanism, denoted a Stronglink, that uses the code imbedded in the Shuttle Mechanism for unlocking. The Stronglink is designed to block a beam of optical energy until unlocked. A Photonic Integrated Circuit (PIC) fabricated in Gallium Arsenide (GaAs) and an ASIC have been designed to read the code contained in the Shuttle Mechanism. The ASIC interprets the data read by the PIC and outputs low-level drive signals for the actuators used by the Stronglink. An off-chip circuit amplifies the drive signals. Once the Stronglink is unlocked, a laser array that is assembled beneath the device is energized and light is transmitted through an aperture.

INTRODUCTION
Funded as an advanced development project, work is underway at Sandia National Laboratories (SNL) to develop a micro trajectory safety subsystem. Our goal is to determine the feasibility of using micro trajectory safety systems for retrofit applications. Trajectory safety subsystems function as an energy gate to a region that contains critical weapon components. They prohibit energy from entering this region, also called an exclusion region, until receiving correctly coded input information—see Figure 1. This information signal is made up of a mixed two-part code; the first part is a 24-bit code entered by the system user, and the second part is a 24-bit code generated as a function of a trajectory environment. These two 24-bit codes are mixed together to form a unique signal that is used to unlock the system and pass energy to critical components. The motivation for this work 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 a catastrophic loss of life, property, or damage to the environment. An example could be the unintended detonation of a weapon system due to a transportation accident or exposure to abnormal environments.

Two mechanical devices are used in our system; the first is an Environmental Sensing Device (ESD) and the second is a locking mechanism known as a Stronglink. The ESD is a device which actuates after sensing an appropriate velocity change by mechanically integrating an acceleration input over time. The device consists of a suspended shuttle that has a long rack at one end and a catch feature used to latch

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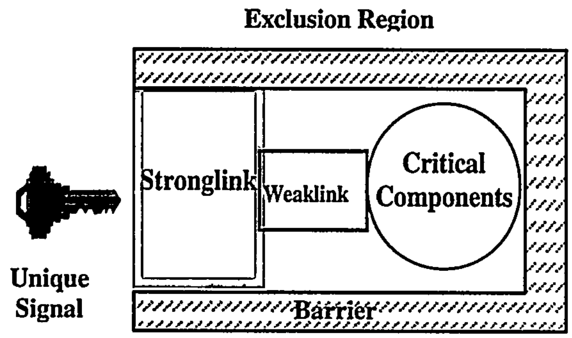

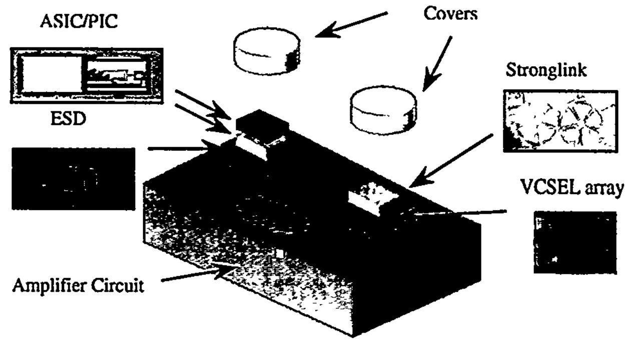

Figure 1. Safety Subsystem Architecture. Figure 2. Trajectory Safety Subsystem Hardware.

the device in place at the other end. Fabricated into the shuttle are four channels of coded information. Mounted above the device is a Photonic Integrated Circuit (PIC) that is fabricated in GaAs and consists of grown lasers, waveguides, mirrors and photo detectors. As the shuttle translates past the PIC, the imbedded code is read and sent to an ASIC. The ASIC converts the coded information into drive signals for the second mechanical device, the Stronglink—see Figure 2.

The Stronglink is a mechanical locking mechanism that blocks energy from entering into a protected volume until receiving a 24-bit code. If the correct code is received, the Stronglink unlocks and an energy coupler mechanism is oriented into proper alignment to pass energy through the device. If the wrong code is received, the Stronglink irrevocably locks up. The stronglink functions as a "mechanical-locked door" in a trajectory safety subsystem.

For this application the allotted volume is 10 mm x 6 mm x 3 mm. The limited volume available necessitated the use of micromachining fabrication technologies. Some of the part sizes and features that are required for these devices push current process capabilities. The work described below represents our progress during the first sixteen months of the project. This paper discusses our accomplishments in the design, fabrication, and testing of two MEMS devices, and the design of a PIC. Fabrication and post processing work are also presented. Our future plans for this project are outlined in the Conclusion section.

SMM MEMS DESIGN

ESD

The ESD system requires three separate components; a mechanical ESD fabricated using MEMS technologies, a PIC fabricated in Gallium Arsenide, and an ASIC fabricated using standard CMOS technology. To actuate the ESD, a centrifuge is needed to supply the required acceleration environment. An ESD-like component that mitigates the need for a centrifuge, but still allows for testing of the PIC and ASIC subassemblies was designed. This device emulates the ESD, but is instead actuated by a rotary actuator. The device, denoted the Shuttle Mechanism, is shown in Figure 3. This design is similar to the ESD design with the exception that a rotary actuator is used in place of a mechanical damping mechanism. At this point in time we have fabricated and tested the Shuttle Mechanism and have just recently submitted the ESD design for fabrication. This paper contains only the details for the Shuttle Mechanism.

The Shuttle Mechanism consists of four major components: a spring suspension, a shuttle with coded information, a rack and pinion transmission, and a Microengine rotary actuator [1,2]. The spring suspension consists of three folded-beam springs nested together. The springs are designed to suspend the shuttle in the plane of fabrication and allow for a 500 μm stroke along the longitudinal direction of the shuttle.

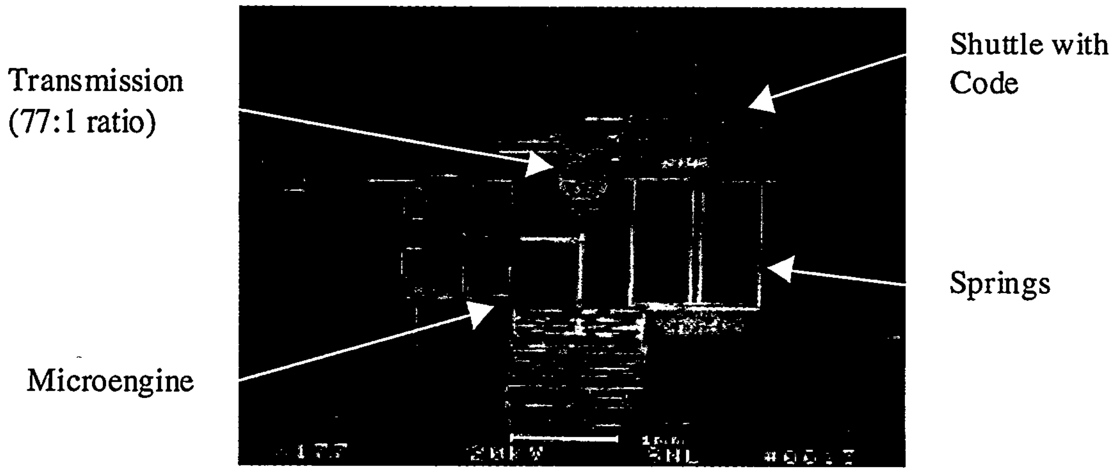

Figure 3. SMM Shuttle Mechanism.

To actuate the device, a rack and pinion transmission system is used with a Microengine rotary actuator. The transmission consists of three stacked gears that are arranged to step up the torque in the system. The gear ratio for the transmission is 77:1. The transmission is designed to provide an output force that is 3.7 times the force (neglecting friction) needed to actuate the shuttle.

The coded information needed to actuate the Stronglink is imbedded in the shuttle. Four optical channels are used; one data line, two clock lines, and a reference line. A PIC is flip-chip mounted above the Shuttle Mechanism and the information is read optically from the shuttle as it translates past the optical circuits. The output from the photo detectors is sent to an ASIC where the logic is interpreted. Quadrature logic is used to read the code that is shown in Figure 4.

The logic is established so that every time a clock channel changes state, the data channel is read. The clock channels are also set up so the first clock always changes state before the second clock. Two clock lines are used so that in the event the shuttle reverses direction the data is not interpreted incorrectly. The reference channel is used by the ASIC to normalize the on and off states of the photo detectors.

To measure the code, a backscatter optical detection scheme is employed [3,4]. Each slot that represents a clock or data bit is fabricated with a series of vanes. Figure 5 depicts this back scatter measurement scheme. The laser light from the PIC is transmitted onto the shuttle at an angle. For the "on" bits, the light reflects off the vanes and returns back toward the source. Surrounding the source are arrays of photo detectors that measure the reflected light. For the "off" bits, areas that do not contain vanes scatter the light forward which is not reflected onto the photo detectors.

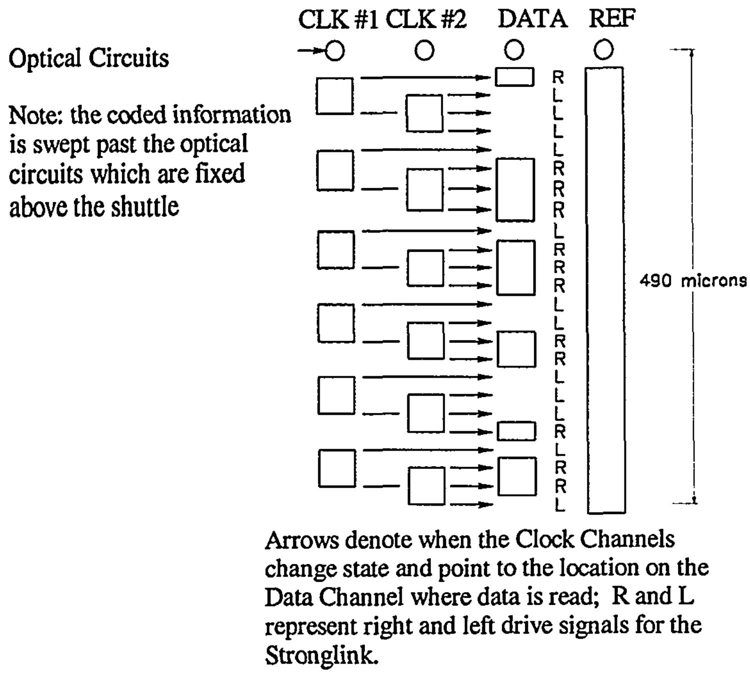

Figure 4. Diagram depicting the logic used by the ASIC.

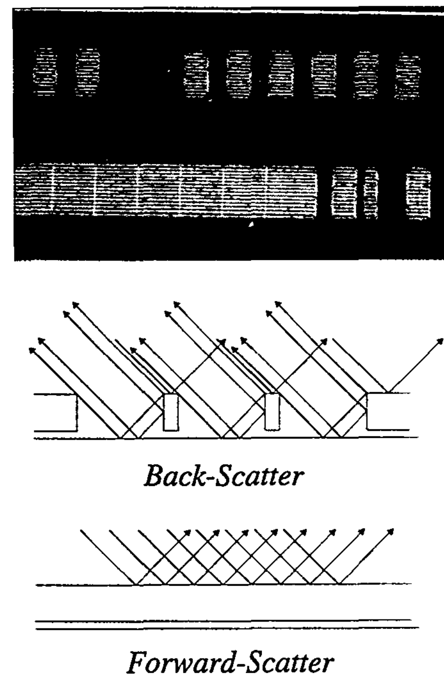

Figure 5. Optical Measurement Scheme.

Stronglink

Figure 6 is a SEM picture of the first SMM Stronglink. The design uses a Counter-Meshing Gears (CMG) discrimination scheme [5]. The CMG discriminator mechanism consists of two separately driven gears and two counter-rotation pawls. Separate rotary actuators are used to drive each gear in the same rotational direction. The gears are rotated in specific rotational increments in a unique sequence. The drive signals for each rotary actuator are supplied by an ASIC. An off-chip amplifier circuit is used to amplify the drive signals before they are sent to the Stronglink.

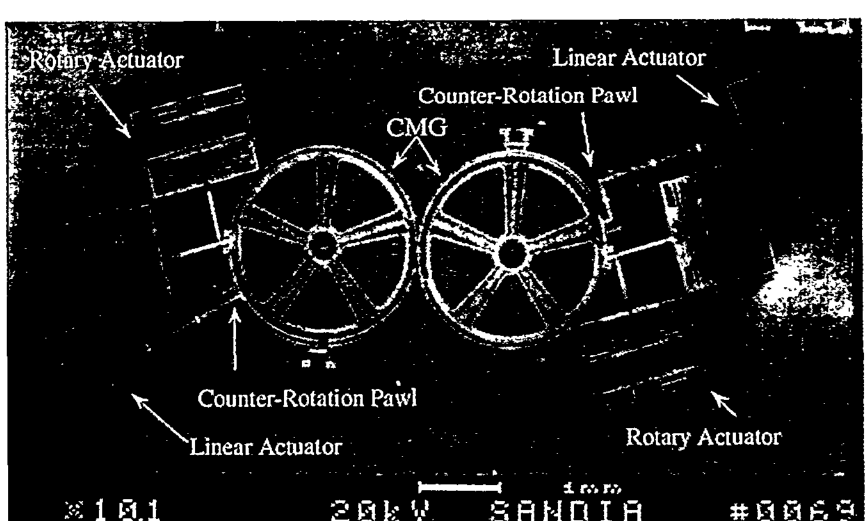

Figure 6. SMM CMG Stronglink.

The gears that make up the CMG discriminator are composite structures consisting of three gear layers. The gear structures are configured so that a coded pattern is developed in 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 Figure 7. 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. This 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. If the wrong indexing sequence is used, the teeth on the composite gears interfere and a device lock-up condition results.

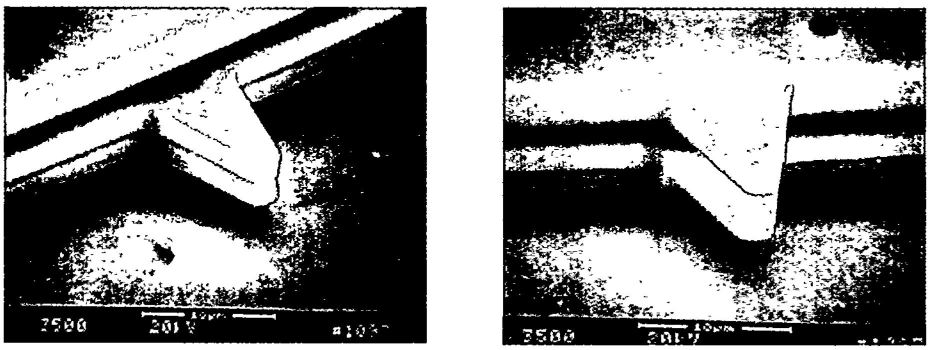

Figure 7. SEM pictures of the discrimination teeth on the CMG Stronglink.

The lock-up feature is accomplished by using counter-rotation pawls, shown in Figure 8. These devices limit the rotation of the gears to one direction. The mechanism consists of a cantilever beam with a gear tooth fabricated on the free end that engages the teeth on the CMG. Positioned next to the tooth on the beam is a fixed stop. As the gear rotates in the counter-clockwise direction, the beam deflects enabling the tooth attached to the beam to ratchet through the teeth on the gear. When the gear is driven in the clockwise direction, the tooth on the free end of the beam is driven into the fixed stop and wedged into position. This action prohibits the gear from turning in the clockwise direction.

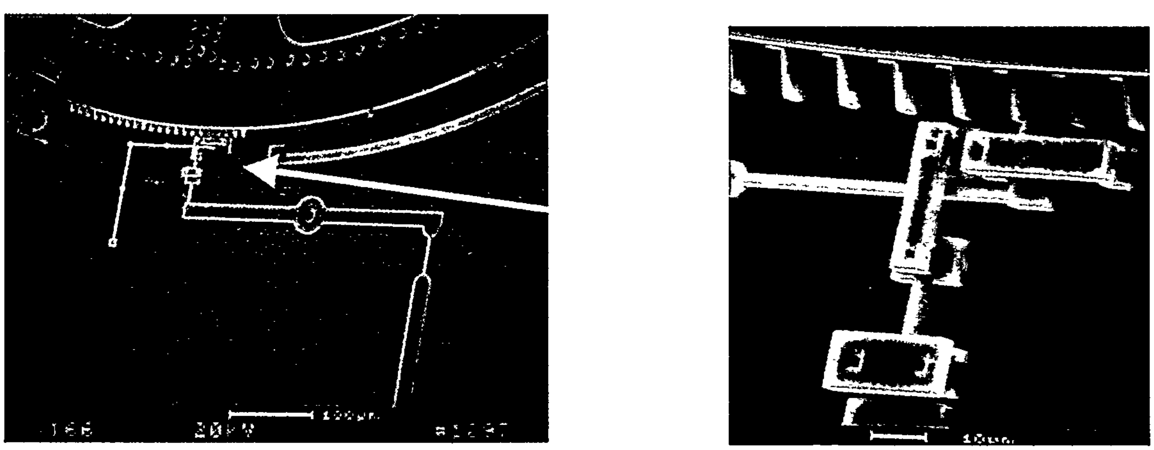

Figure 8. Counter-Rotation Pawl.

The Stronglink is designed to block optical energy until unlocked. A 100 μm diameter aperture is fabricated in the left gear. Prior to releasing the device, a deep silicon etching post process (BOSCH etching) is performed on the backside of the die to form a via through the silicon substrate. During the packaging step, a Vertical Cavity Surface Emitting Laser (VCSEL) array is mounted below the device in a submount. When the Stronglink is unlocked, the aperture is rotated into alignment position and the VCSEL array is energized. Optical energy is then transmitted through the backside via and the aperture.

MEMS FABRICATION AND POST PROCESSING

Sandia' four-level SUMMiT process is used to fabricate the MEMS devices [6]. A cross-sectional view of a pair of stacked gears depicting the layer thickness is shown in Figure 9. Four polysilicon layers are used. The first poly layer serves as an electrical ground plane. The remaining three layers are used to fabricate mechanical structural elements. Chemical Mechanical Polishing (CMP) is used to planarize the third sacrificial oxide layer. The CMP step improves the designer's flexibility by eliminating the need to compensate for conformal underlying layer topology for features designed in the third polysilicon layer. Dimples or standoffs are fabricated in the first polysilicon layer to reduce friction problems between the gear and the substrate and constrain the gear so that meshing with a mating gear is always achieved. After the parts are released a SAM coating known as PFTS is applied to the device to provide a friction reduction coating [7,8]. Typical fabrication run times are 4 months.

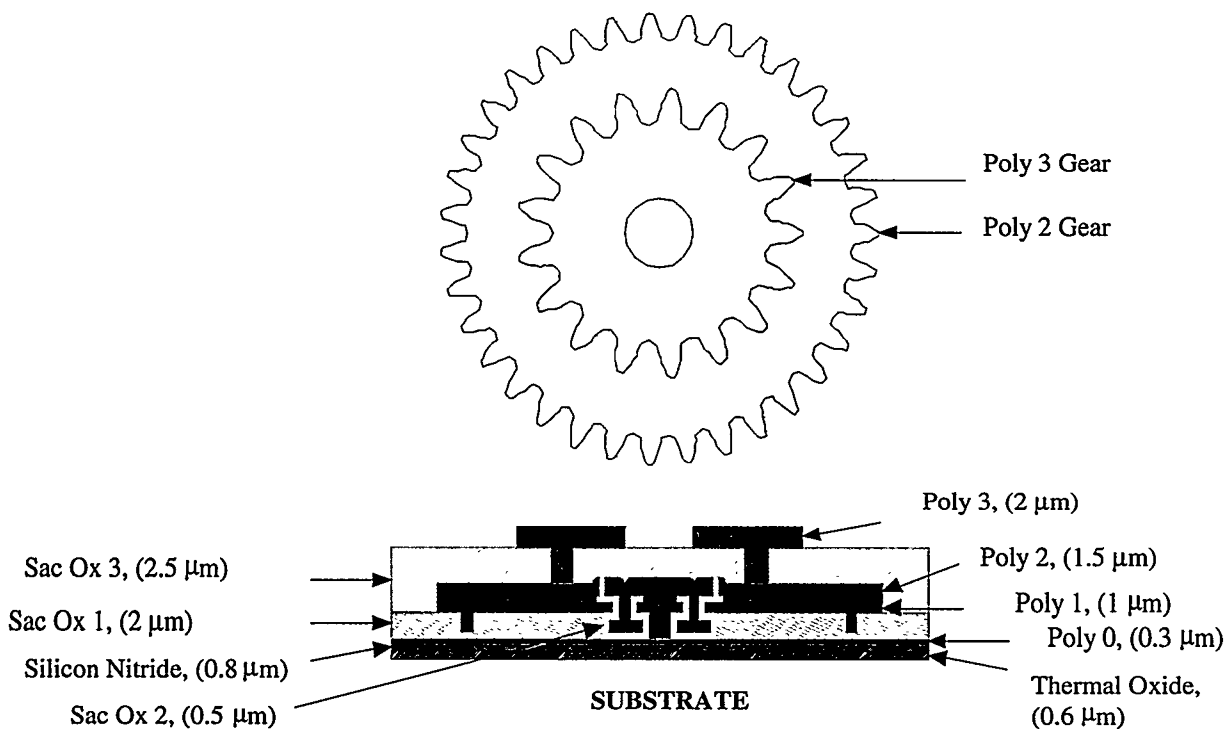

Figure 9. Cross-sectional view of a set of gears fabricated using the SUMMiT process.

The CMG device requires post processing to provide a via for optical energy. The via is machined in the backside of the silicon wafer by a Deep Reactive Ion Etch (DRIE) process commonly known as the BOSCH process [9]. A DRIE BOSCH etched hole is shown in Figure 10. First the backside of the wafer is lapped and polished to expose the silicon substrate. Photoresist is spun on the front side of the device to form a protective layer. Next, photoresist is spun on the backside and a pattern step follows. The patterned wafer is then exposed to the DRIE process and the silicon substrate is etched. The thermal oxide deposited on the front side of the wafer during the SUMMiT process is used as the etch stop due to etch selectivity of ~250:1 (Si:thermal oxide). Finally the device is removed and the photoresist stripped off. The sacrificial oxide is wet etched away in the final release process and the device is coated with PFTS.

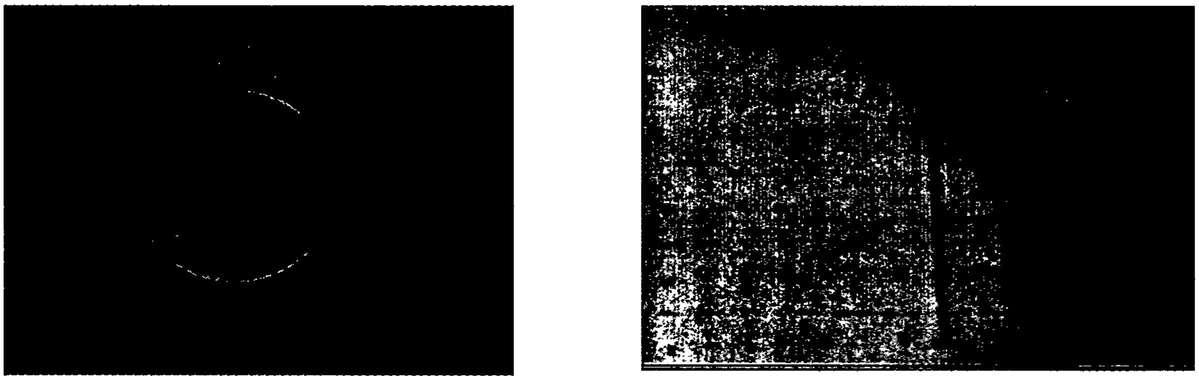

Figure 10. DRIE BOSCH etched hole in the backside of a silicon wafer that contains MEMS components the front side.

The Shuttle Mechanism requires a gold layer to improve reflectivity. A gold film 2000 Å thick is evaporated on the shuttle by a shadow masking process. Figure 11 shows the gold layer deposited on the shuttle. Currently we are pursuing a gold lift-off process where the gold can be lithographically defined. Patterning will also enable us to deposit a metal layer on our electrical bond pads. This step will improve the strength of our electrical wire bonds.

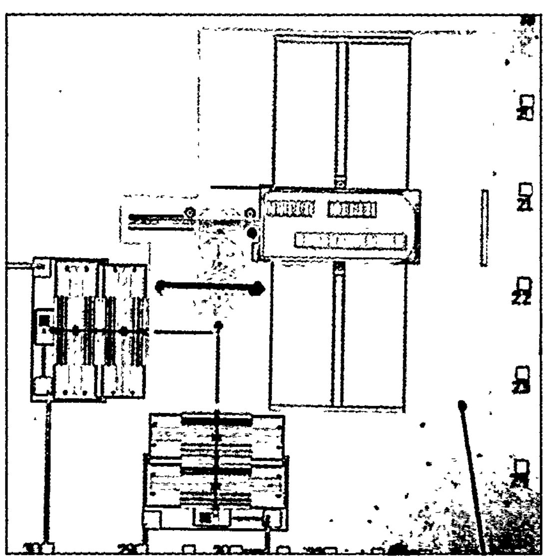

Figure 11. Shuttle with gold added for reflectivity.

PHOTONIC INTEGRATED CIRCUIT

The PIC design consists of four primary components, a laser, four waveguides, four mirrors and four arrays of photo detectors. The PIC is fabricated in GaAs at Sandia's Compound Semiconductor Research Laboratory (CSRL). The design pushes the process capabilities. A laser is grown using a selective area regrowth process on a GaAs wafer. Attached to this laser and branching out across the wafer is a waveguide network that consists of a wave splitting mechanism (splitter) with four branches. Four branches are used to measure the four channels of data fabricated in the shuttle. At the termination of each branch, a mirror is fabricated with a 22.5 degree angle. Each branch therefore steers a beam off the wafer at 45 degrees, with respect to the plane of fabrication. The light is projected onto the MEMS shuttle that is mounted directly below the PIC. When the slots with vanes that represent the coded information on the shuttle are aligned beneath a beam of light, a backscatter reflection occurs where the light is reflected off the substrate and sides of the vanes in the slot.

Fabricated around the mirrors on the PIC are arrays of photo detectors. The reflected light projects back from the shuttle onto the photo detector arrays and is converted to electrical currents. These currents are sent to an ASIC where they are interpreted. As the two clock lines separately change state (clock two always lagging clock one), the data channel is read. When a backscatter readout occurs, the ASIC interprets an "on signal" and generates a drive signal for the right motor on the Stronglink. Conversely, when the data channel is read at a position where the light is scattered forward, the ASIC interprets an "off signal" and generates a signal for the left motor on the Stronglink. As the data is read one bit at a time, the Stronglink unlocks one bit at a time. Once the 24^{th} bit is read, the Stronglink is unlocked and the aperture is rotated into position to align directly over the VCSEL array which is then energized and light passes through the aperture.

Fabrication activities are currently ongoing for the PIC design. At completion, the PIC will be integrated into a package with the MEMS Shuttle Mechanism and ASIC, where it will be flip-chip mounted above the MEMS device. Electrical connection to the ASIC will be accomplished with a wedge wire bonding tool.

RESULTS

The SMM Shuttle Mechanism has been fabricated and tested. We were able to drive the shuttle through the full 500 μm stroke; however, we encountered an intermittent problem. A gear in the transmission tilted out of the plane of fabrication during operation and engagement with the mating gear was temporarily lost. A tolerance analysis revealed the shaft diameter was too small thus permitting a 3 μm out-of-plane deflection at the edge of the gear. To fix the problem a larger gear hub and an outer support structure were added to the design to limit the deflection to 0.6 μm. At this time, fabrication activities are ongoing for this modification. To salvage the parts on hand, we designed a guide that limits the tilt angle to 1 μm. The guide was fabricated from epitaxial silicon using the BOSCH etching process. Guides were assembled over the transmissions and bonded into place with RTV adhesive. The silicon guides work very well and completely remedy the tilting problem.

We designed an ASIC that would receive the information signals from the PIC and output drive signals to the Stronglink. The ASIC was fabricated using a standard CMOS 1.2 μm (line width) process where two, polysilicon layers and two metal layers were deposited. Test results revealed that lower threshold currents could be measured than our initial requirements. We were thus able to detect currents in the hundreds of pico-amp range. This capability enhanced our detection measurement scheme. We packaged the ASIC and Shuttle Mechanism in a commercially procured 40 pin DIP package using a JM7000 cyanite-ester epoxy. The electrical leads were then wire bonded. Next we conducted functionality tests on both packaged devices with successful results. Once the PIC has been fabricated, it will be flip-chip mounted above the MEMS device and the electrical leads wire bonded to the ASIC. An amplification circuit that amplifies the drive signals generated by the ASIC was also designed, fabricated, and tested. Figure 12 shows the amplification circuit with the packaged MEMS and ASIC devices.

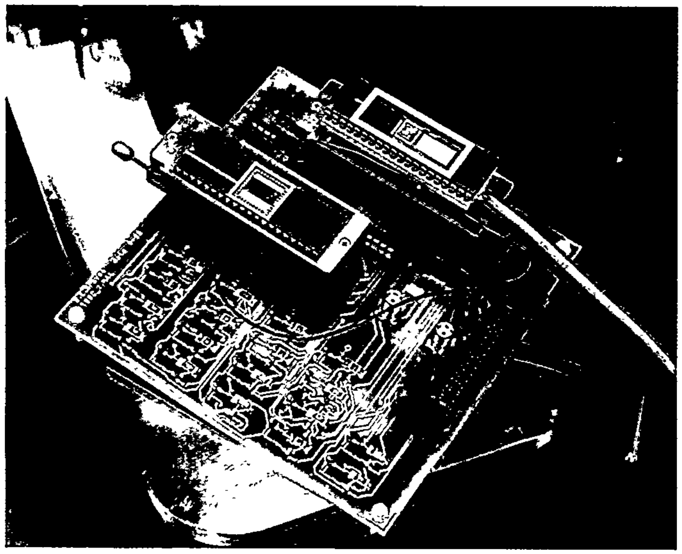

Figure 12. Assembled hardware with amplification circuit.

The Stronglink was post-processed to fabricate a through-via from the backside of the wafer and then released and SAM coated. A VCSEL array fabricated in Sandia's CSRL was mounted in a submount and bonded to a 40 pin DIP package. The electrical leads were then wire bonded to the package. Next the Stronglink was aligned and attached to the top of the VCSEL submount assembly. Functionality tests were conducted on both components with successful results. The wavelength of the light from the VCSELs is 670 nm.

While awaiting the completion of the PIC, we fabricated a code reading device that emulates the shuttle and PIC assembly and interfaces to the ASIC. The device consists of four photo diodes and four photo detectors arranged so that each photo diode is positioned in front of a photo detector. An aluminum plate was machined with coded information to unlock the Stronglink fabricated on the surface. The coded plate is swept across the photo detector and photo diode assembly and the electrical currents from the photo detectors are sent to the ASIC. The ASIC then interprets the information and sends drive signals through the amplification circuit to the Stronglink. The Stronglink actuates and the VCSEL array is then energized. We successfully conducted this demonstration with our packaged ASIC and VCSEL/Stronglink assemblies.

CONCLUSIONS

Our goal for this project is to develop a micro trajectory safety subsystem. To accomplish this we are using SMM fabrication technologies to fabricate two mechanical devices and compound semiconductor processes to fabricate a PIC. Two SMM MEMS devices have been designed, fabricated, and successfully tested. We have also completed a design for a PIC that is now in fabrication. To process optical information from the PIC and to generate the appropriate Stronglink drive signals, an ASIC has been designed and fabricated using standard CMOS 1.2 μm processing. The drive signals from the ASIC must be amplified before being outputted to the Stronglink. An amplification circuit has been designed and fabricated for this purpose. We have successfully packaged the MEMS devices, the ASIC, and VCSEL array in commercially procured packages. A wire bonding process was used to provide electrical connections from the packages to the mounted hardware. To test the ASIC, Stronglink, and VSCEL subassemblies, an optical code-reading mechanism was developed that emulates the Shuttle Mechanism and PIC assemblies. Test results of the operation of the packaged ASIC, Stronglink, and VCSEL assemblies were successful using the code-reading device as the source for the code.

We have made significant progress towards our goal of developing a micro trajectory safety subsystem. The final system will contain an ESD actuated by an acceleration environment. We have recently completed the design for such a device that requires fabrication using Sandia's five-level polysilicon process. We plan to report our results later, as this part of the project matures. There are a number of issues that have not been addressed at this point in time. Namely, we have not subjected our system to environmental testing such as mechanical shock, vibration, and sub-ambient and elevated thermal tests. We plan to conduct these experiments in the near future. Also, a package that fulfills our volume requirement of 10 mm x 6 mm x 3 mm has not been designed. A package design is currently being developed.

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