DEVELOPMENT OF INEXPENSIVE, ULTRA-MINIATURE MEMS-BASED SAFETY AND ARMING (S&A) DEVICE FOR SMALL-CALIBER MUNITION FUZES

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ABSTRACT

The development and demonstration of an inertially-operated micro-electro-mechanical systems (MEMS) mechanical safety and arming (S&A) device for artillery and small caliber fuzing has proceeded through concept, analysis, design, initial prototyping, and ballistic demonstration phases. This paper summarizes the implementation of "microscale inertial mechanical logic" for mechanical safety and arming functions in the form of sliders, rotors, latches, springs, and locks that interact on a planar substrate in response to inertially-induced forces, and the technical/fabrication issues encountered in the process. The program is sponsored by the U.S. Army TACOM ARDEC Joint Services Small Arms Program (JSSAP) Office, under the Objective Individual Combat Weapon (OICW) Systems Enhancements Science and Technology Objective (STO). The goal is to rapidly develop, demonstrate and transition lethality-enhancing and weight/cost-reducing technologies into the OICW system to ensure Objective Force Battlefield superiority.

1. INTRODUCTION

The U.S. Army Tank-automotive & Armaments Command Armament Research, Development, and Engineering Center (TACOM ARDEC) Close Combat Armament Center (CCAC) Fuze Division has developed prototype MEMS-based mechanical safety and arming (S&A) devices for a 20-mm high-explosive bursting round (HEAB) under the sponsorship of the JSSAP Office's OICW System Enhancements STO. The design is for a 20-mm air-bursting munition having a mid-body fuze and dual warhead design. The munition fuze is inductively programmed in the weapon and uses a turns count for arming. Nominal muzzle velocity is 231 m/s, with peak acceleration of up to 65k G's, and a muzzle spin rate of 490 rps.

The goal of the work is to reduce the cost and volume of the S&A device by mapping the well-established design principles for mechanical safety and arming systems into the planar domain using micro-electro-mechanical systems (MEMS) fabrication technology. The cost reduction comes from the economies of high-volume production using the wafer-type processing of the semiconductor industry, including microscale mold-transfer replication techniques, and novel batch wafer techniques for explosive loading. The reduction in volume allows more payload and thus make small-caliber rounds more effective (lethality) and the weapon system more affordable (sustainability). The MEMS S&A is scheduled to transition to the warfighter in FY08. If successful, this transformational technology will support the Objective Force Warrior by increasing lethality and survivability, and will be able to support other small-caliber fuze systems. It will also assist the fuze community by moving some of the production out of the shrinking small-parts industrial base and into a growing MEMS production base.

The MEMS S&A works by incorporating the functions of a conventional "watchworks assembly" type mechanical S&A in a single inertially-actuated "mechanical logic" S&A chip that controls the components of a specially-developed explosive microscale firetrain (MSF) and that can integrate directly with the fuze circuit. The MEMS S&A assembly consists of sliders, rotors, latches, springs, and locks that interact on a planar substrate in response to the inertially-induced forces of launch. Its ultimate function is to move a critical element of the firetrain in-line with an output explosive lead. The explosive output of the assembled device is equivalent to that of a standard detonator.

This paper reviews the technical experience, problems, and results obtained in applying MEMS technology to the problem of realizing ultra-miniature inertial mechanical logic designs.

2. APPROACH

Starting with the design rules particular to selected high-aspect-ratio (HAR) MEMS fabrication technologies, "mechanical safety logic" was developed that could be implemented in a planar wafer-type format using components inter-operating on a substrate. Beginning with design and optimization of the components themselves, the work was carried through several generations of design, analysis, fabrication, and laboratory testing of the components, and then the effort was expanded to include assemblies that were flight tested in 20- and 40-mm projectiles. In parallel, a compatible micro-scale interrupted firetrain was developed and laboratory demonstrated whose detonation output could be controlled using the above implementation of mechanical safety logic operating in a launch environment.

3. MEMS TECHNOLOGY

MEMS fabrication technologies were surveyed for their potential to meet the technical and cost requirements of prototyping an inexpensive MEMS-based S&A device. A technology was needed that would provide high-aspect-ratio, vertical-sidewall MEMS parts on the order of 100-1000 μm thick to accommodate a movable firetrain element, with mechanical features as small as 10-μm, and producing releasable parts. These parts must also be rugged enough to function in 100,000 Gs, and must have the potential for wafer-level assembly, mold transfer replication, and long shelf life. Our survey included technologies such as high voltage electron beam lithography, laser micro-machining, deep reactive ion etching (DRIE) of silicon, standard and UV-based LIGA micromachining of nickel, electrochemical fabrication (EFAB), and two types of plastic replication. Of the above, only DRIE and LIGA methods offered the needed combination of feature resolution, vertical sidewalls, thickness, availability of commercial sources, and affordable cost.

DRIE processing of silicon involves plasma-phase etching in a special chamber, using reactive ions that are accelerated under an electric or magnetic field towards a mask-pattern-defined target substrate. The target substrate is generally a sandwich of two silicon wafers with an insulating layer of silicon dioxide in between them, called a silicon-on-insulator (SOI) wafer. This technology can anisotropically etch vertical-walled trenches all the way through the top wafer down to the insulator layer, using alternating etch and passivation steps, at rates exceeding 1-μm/min. [1]. Parts can be freed from the substrate by chemically removing the silicon-dioxide bond layer. This often requires that etch-release holes be designed into the otherwise solid pieces that are to be released, to allow the etchant access to the bond layer. This produces geometries made of single-crystal silicon, with some parts (the "frames") remaining fixed to the substrate, and others, hopefully the intended ones, being released from the substrate to become "working" or movable parts in the assembly. Making the moving parts together in the same process as the fixed parts is referred to here as 'in situ' fabrication.

The LIGA (Lithographie, Galvanoformung, Abformung) process was invented in Germany, and uses high-energy x-ray radiation from a synchrotron source to expose a deep photoresist layer through a special mask. When the resist is chemically developed, a three-dimensional mold structure is formed, into which metal can then be electroplated. After photoresist removal, a freestanding metal structure remains. These metal structures can be used directly, or they themselves can be used to mold replica parts in another material [2]. If working parts are formed in situ with the frames, they can be released in a process similar to that used to release the DRIE parts, by incorporating the same type of etch-release holes and a liquid phase etch process.

By utilizing high-aspect ratio processes, this work employs fabrication methods distinct from those involved in developing inertial sensors such as off-the-shelf MEMS-based accelerometers or gyroscopes, which typically combine surface micromachining technology with on-chip or flip-chip signal circuitry. Nor does this work attempt to make off-the-shelf MEMS-based actuators such as microscale valves or inkjet print heads. Rather, the goal was to prototype a mechanical logic device and assembly whose components intrinsically combine both sense and actuate functions in a single unpowered chip that performs the functions of a mechanical S&A device.

4. MECHANICAL S&A CONCEPT, DESIGN, AND ANALYSIS

To perform the safety and arming functions of a mechanical S&A, the MEMS-based S&A must incorporate two independent safety features, each of which shall prevent unintentional arming of the fuze [3]. Furthermore, the stimuli to enable such safety features must come from two independent environments, and these environments should not be of a sort that the fuze could normally encounter prior to intended launch.

The technical challenge was to shrink mechanical functions involving sequential actions of inertially-activated interlocking elements into the micro-scale, or MEMS, domain. MEMS features were realized using etch, pattern, mold, and release techniques on a planar wafer substrate, processes common in the semiconductor industry, to yield features in a range from 10-µm to several millimeters in size. **Figure 1** shows the basic design of the inertial-mechanical logic for a MEMS mechanical S&A device [4]

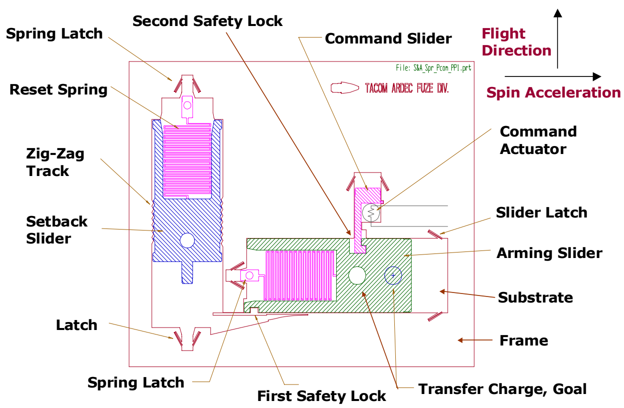

Figure 1. Basic MEMS S&A design, transfer charge in the safe position.

The basic MEMS S&A design consists of a spring-biased setback slider, a setback lock lever, a spring-biased command slider, an arming slider, and a command actuator, all moving about on a substrate and confined to operate within tracks imposed by a "frame" that is attached to the substrate [5]. The arming slider controls the position of an explosive-train element called a transfer charge that is held out-of-line with the firetrain until arming occurs. The transfer charge must be of a certain thickness to have any effect, therefore high-aspect- ratio (HAR) MEMS technology (100 to 1000-µm thickness) is required. Before packaging, the spring heads must be brought up into their latch sockets to pre-tension the springs, biasing the sliders toward inaction. The command actuator, notional at this point, works by the expansion of a propellant charge pushing it as a piston, but other methods of actuation are under development.

The arming slider's position is controlled by the two mechanical locks, which must operate in the proper sequence, and also by two forces: centrifugal force due to spin of the projectile, and spring force exerted by a pre-biased reset spring. The proper sequence is for the setback slider to go downward against spring tension and zig-zag delay timing and lock (due to launch setback), and disengage the setback lock lever from the arming slider. Then the arming slider can move to the right under spin acceleration to enable the command slider. The command slider in its starting position will stop the arming slider motion once its foot has cleared the overhang in the arming slider pocket, whereupon the command slider is enabled. When the command slider is actuated upwards, its foot clears the arming slider, and under the influence of continued spin acceleration the arming slider moves right, against spring tension, and latches, putting the transfer charge in the armed position. Notice that if the command slider actuates prematurely, or spin is not present, or there is insufficient setback, the system either stays safe or fails safe. This basic mechanical logic complies with the above-mentioned standards of fuze design and safety. The system is shown post-launch with components deflected to the armed position in **figure 2**.

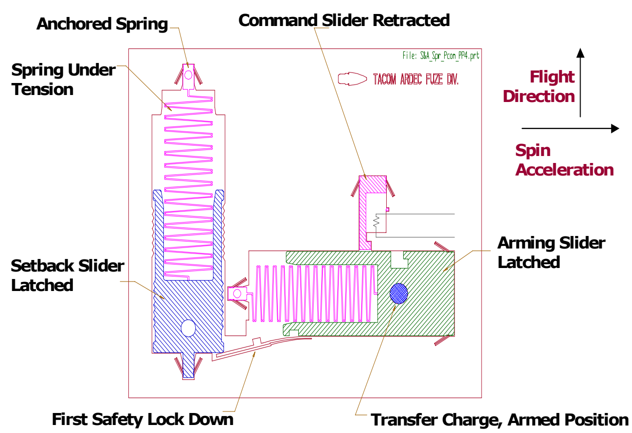

Figure 2. Basic MEMS S&A design, components in the armed position.

In **Figure** 3 the project flow shows how the development of the MEMS-based S&A started with a review of the design-rule set for two forms of HAR MEMS technology, DRIE and LIGA. Design rules specify allowable feature size, gap size, depth, etc. Mechanical-inertial

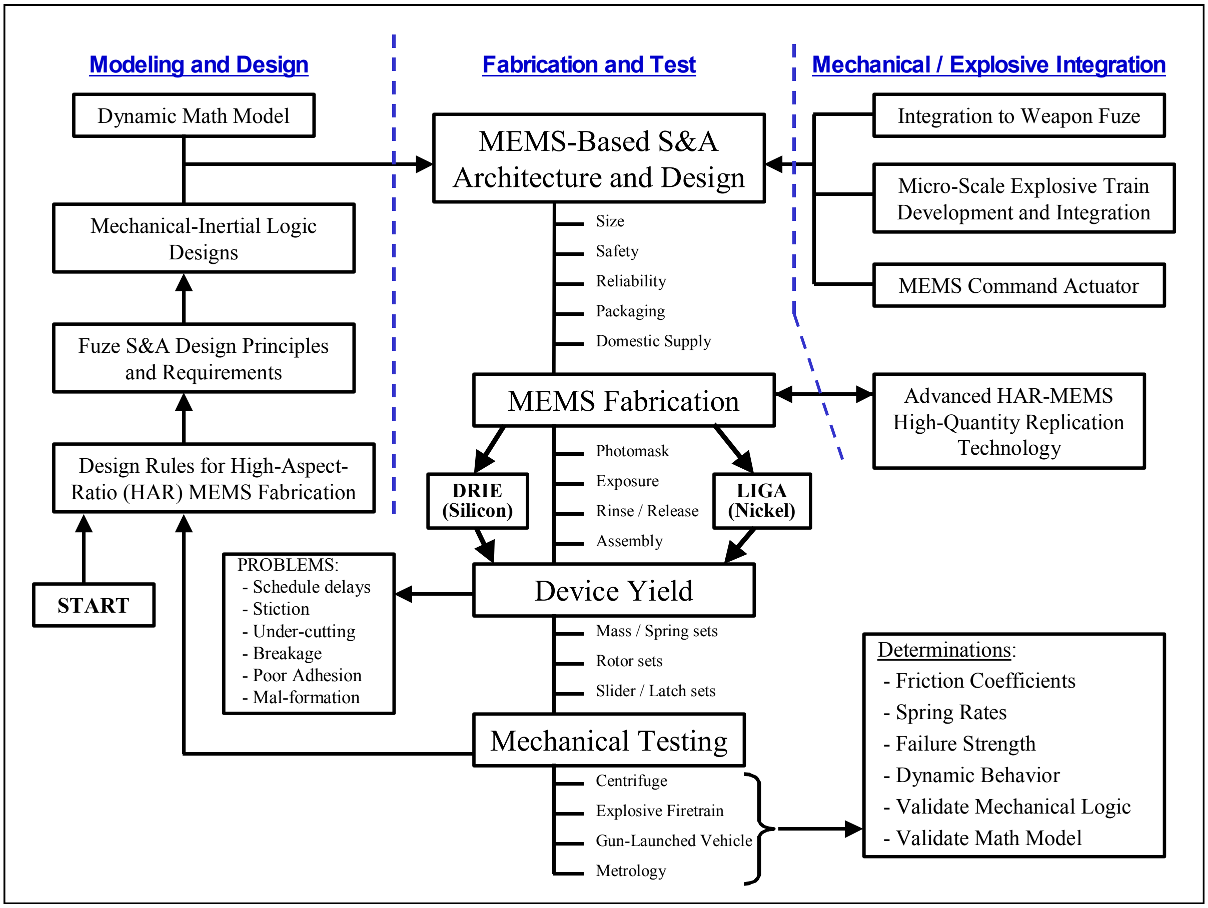

Figure 3. Block diagram of MEMS S&A development process.

logic designs incorporating the principles of fuze S&A design were developed and math modeled before committing to the "MEMS-Based S&A Architecture and Design" block shown in the figure. Other requirements had to be met as well: integration of a developmental microscale firetrain, integration with the weapon system, and incorporation of a command actuator.

5. DEVICE FABRICATION

Fabrication using DRIE and LIGA technology was accomplished at various MEMS foundries accessed through the CNRI MEMS Exchange network, based in Reston, VA, including LIGA work done at Axsun Technologies, Livermore, CA.

5.1 DRIE Process

The first generation of hardware was made using 100-µm DRIE silicon technology to provide parts and assemblies for testing out safety geometries and developing and validating a math model of the system. Using DRIE silicon technology, we fabricated a large number of devices, most particularly zig-zag (inertial delay) sliders, bias springs, latches, rotors and interlocks, but also test devices such as simple spring-mass sets. **Figure 4** shows a scanning-electron micrograph (SEM) of a 20-µm silicon spring, rising 100-µm above the silicon substrate, with a spring biasing latch and receptacle. **Figure 5** shows a portion of a zig-zag delay slider with its bias spring, of the same dimensions. The slider has a regular pattern of square holes in it that are used to chemically dissolve a bond layer beneath the slider, to free the slider from the substrate. A a parametric study of release-etch hole patterns was performed to determine the optimum pattern for doing a "release etch" of working parts and sliders—determining finding that 20 x 20-µm holes on 100-µm centers worked well for our geometries. Note that in this hardware iteration all parts and features were created "in situ", meaning the working parts and frames were fabricated together in the same process.

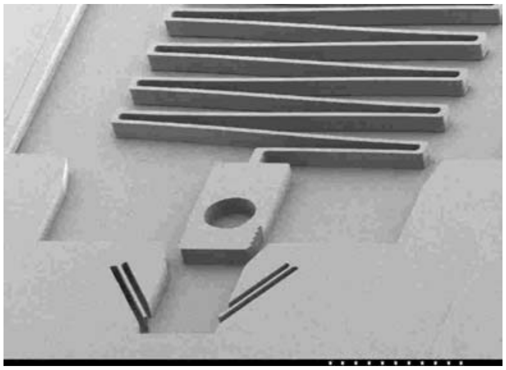

Figure 4. DRIE reset spring bias latch, 100-μm thick.

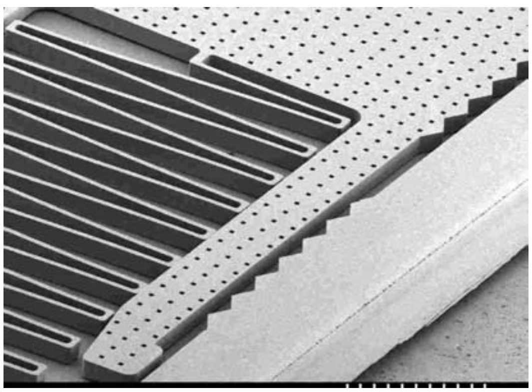

Figure 5. DRIE zig-zag slider mass and spring, 100-μm thick.

5.2 Results of the DRIE Process

The DRIE process produced well-defined geometries, with vertical sides, and with springs that could safely be elongated to twice their starting length. Nonetheless, problems were encountered. Viewed from the top, a section of one of the 40-μm springs appears in the SEM of **figure 6**. However, when the slider mass and spring are inverted to view the underside, as shown in **figure 7**, flaws were apparent. Due to "undercutting", the underside of the spring was tapered and rounded. The effect and condition of undercutting is shown even more graphically in **figure 8**. Comparing the measured thickness of the taper with the nominal thickness, there was a 29% taper. This resulted in springs that were too weak. Other issues and difficulties encountered with the DRIE fabrication process included the following:

a. There was a problem maintaining uniform etch density across the face of the fabrication wafer. The vertical etch rate depends on gas ion density, which is affected by the amount of etching to be done in a local area or the on the diffusion rate down a small hole. We found that the main features geometries as diverse as 20-μm springs and millimeter-wide sliders etched at different rates. For example the time required to finish etching a slow feature, such as a gap between sliders, resulted in the observed undercutting of the springs, where the etch plasma had time to begin working sideways.
b. In some places the geometries were formed correctly, but the release etch process failed, particularly under the sliders. It was difficult to get enough release etchant to diffuse down the release holes to successfully dissolve the silicon-dioxide bond layer. The result of incomplete removal of the bond layer was that some sliders remained firmly stuck to the substrate.
c. Then some of the successfully released sliders spontaneously re-adhered to the substrate. Methods such as "super-critical CO2 etch" were used with some success to prevent this, but even after such treatment some sliders re-adhered.
d. On the positive side, the sidewalls of the DRIE parts appear to be adequately vertical and smooth enough for action. In a series of centrifuge tests, we observed frictional "stick-slip" behavior as spinrate changed to determined static and dynamic friction coefficients of the materials: 0.42 and 0.28, respectively.
e. Also, the single-crystal silicon springs created in this process were linear and could be flexed to more than twice their original length on a centrifuge without breaking. However, when these same springs were more rapidly exercised over the same range of extension in an air-gun impact test, they tended to fracture in many places.

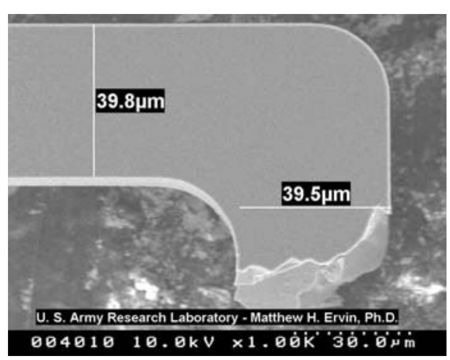

Figure 6. Top of 40-μm spring.

f. Our fabrication yield (successful parts divided by parts attempted) with 'in situ' DRIE was about 20%

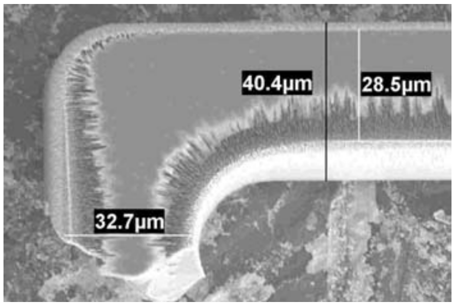

Figure 7. Underside of 40-µm spring, showing undercutting.

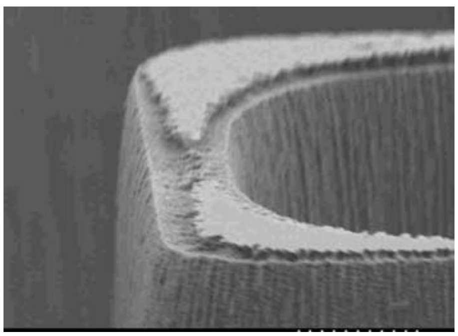
Figure 8. Perspective view of undercut spring.

In spite of these difficulties, the quantity of successful parts such as mass/spring sets, rotor sets, and slider/latch sets which were produced using DRIE micromachining was sufficient to perform mechanical testing using centrifuge, air gun, and gun launch techniques. From this testing we were able to determine friction coefficients, validate latch and spring designs, and demonstrate the mechanical-inertial logic of the S&A scheme.

5.3 LIGA Process

LIGA fabrication of nickel parts offered advantages associated with its material properties of ductility and density. Because its density is more than three times greater than that of silicon, the inertially-actuated parts of a LIGA-nickel assembly could be made smaller than with silicon. And because of ductility, the springs and other features would fail gradually by yielding rather than suddenly by rupture. A re-design was required to adapt the S&A architectures to nickel fabrication, partly because of the material characteristics as noted, but also because of the different fabrication design rules and principles used in LIGA. One version of the redesigned S&A device, including additional sliders and interlocks, is shown in **figure 9.**

5.3.1 First LIGA Iteration

The first generation of LIGA parts involved forming the working parts 'in situ' with the 'frames' on a silicon wafer substrate. The geometries were formed well as evidenced in **figure 9**, but there were difficulties:

1) The release etch process gave inconsistent results in that it proved difficult to release the larger parts such as the setback and arming sliders from the substrate and to prevent re-adhering;
2) When an opportunity arose to piggyback our hardware on a 45,000-G air-gun impact test, we assembled LIGA-nickel parts and DRIE-fabricated silicon frames on silicon wafer substrates, like the assembly in **figure 9**, and flew four assemblies. In one assembly the setback and spin sliders successfully released the locks on the arming slider, which demonstrated operation of the mechanical logic. In the other three assemblies, however, there was some cracking of the silicon substrate and in features of the silicon frame as shown by comparing the pre-flight photo of a slider, spring, and silicon zig-zag track in **figure 10** with the post-flight photo of **figure 11**. The latter figure spring has extended, and the zig-zag track was chipped.

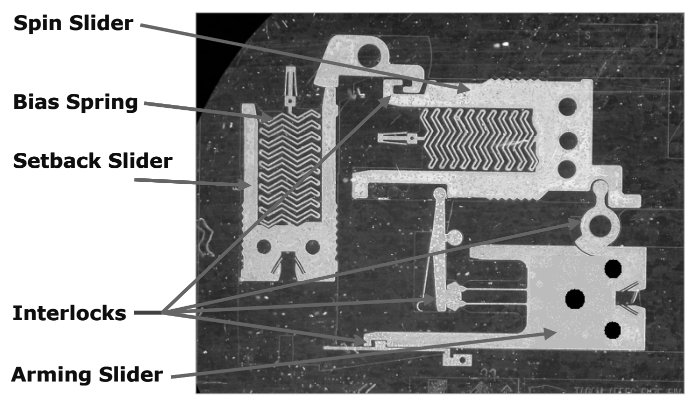

Figure 9. Three-slider, four-lock, 12x15-mm design.

5.3.2 Second LIGA Iteration

In the second LIGA iteration our first change was that we fabricated the working parts in a separate process from the frames. By doing this,

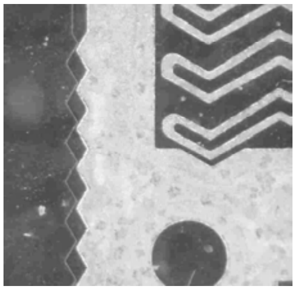

Figure 10. Nickel zig-zag slider mass and spring, with silicon frame and substrate.

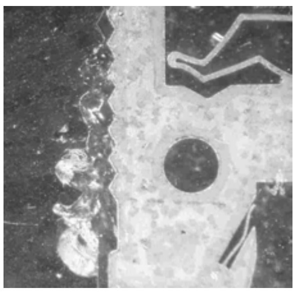

Figure 11. Similar nickel zig-zag slider mass and latch, post-flight.

they could be more optimally released from the silicon substrate. That is, the bond layer under the nickel parts could be dissolved 'to extinction' by leaving the parts in the bath with agitation for as long as needed. This produced very clean parts that could be examined on both sides and sorted according to quality. The drawback was that with parts no longer being created in situ, manual gathering, inspection, and assembly of the parts into the separately-produced frames would be necessary.

Second, we eliminated all silicon in the assembly by fabricating the LIGA nickel frames on a metal substrate. By this method, both frames and their substrates would be made of a tough, resilient material not subject to the type of impact-induced fractures we saw with the silicon substrates and frames.

Finally, we explored new S&A geometries with more interlocks and sliders, and with a thermal actuator, such as the pre-launch assembly shown in **figure 12.** Note that the setback slider is up, and the arming slider is in the safe position. The figure also indicates what part is "substrate," and what part is "frame." After gun-launch aboard a 40-mm grenade (25,000 Gs peak in-bore acceleration) the components were found deployed as shown in **figure 13**, with the setback slider down, the locks released, and the arming slider latched in the armed position.

In summary, the second LIGA iteration produced well-defined, durable, shiny parts and frames of high dimensional accuracy, and an overall yield of better than 80%. By moving to all-metal fabrication, with metal parts operating in metal frames affixed to metal substrates, we were able to demonstrate gun-rugged prototypes of a MEMS-based mechanical S&A. We have since found the frames so rugged that we may shoot them more than once (no explosives), simply replacing any expended parts such as springs. MEMS hardware from the second LIGA iteration was used in the flight tests described in section 7.

6. MICROSCALE FIRETRAIN DEVELOPMENT AND TESTING

Components of the microscale firetrain were developed and demonstrated at the Naval Air Warfare Center (NAWC), China Lake. **Figure 14** shows a stackup of spacers and holders used to reproduce the thickness and spacing of the MEMS assembly, and to perform partial arming, in-line, and out-of-line testing against a dent block. Not shown are additional assemblies using actual MEMS S&A hardware to perform similar successful demonstrations.

7. FLIGHT TESTING AND RESULTS

The following ballistic tests were performed with LIGA-fabricated MEMS assemblies consisting of nickel parts operating in nickel frames on copper substrates. The command slider was left inactive in all rounds, though in some cases the actuator parts were included for observation.

7.1 Gun Firing in a 40-mm Grenade

On 04 Apr 2002 prototype MEMS-based mechanical S&A devices were demonstrated in a ballistic test of twelve assemblies using the Army Research Laboratory test facility at Blossom Point, MD. The devices were fired from a MK19 40-mm Grenade Machine Gun, achieving approximately 42,000 Gs peak acceleration and 200 rps spin in the tube. The test was conducted with a soft catch to enable recovery and analysis. Eight of the twelve recovered units fully armed as intended with no signs of damage to components. Three of the first four units had setback-lock shear tabs that were too

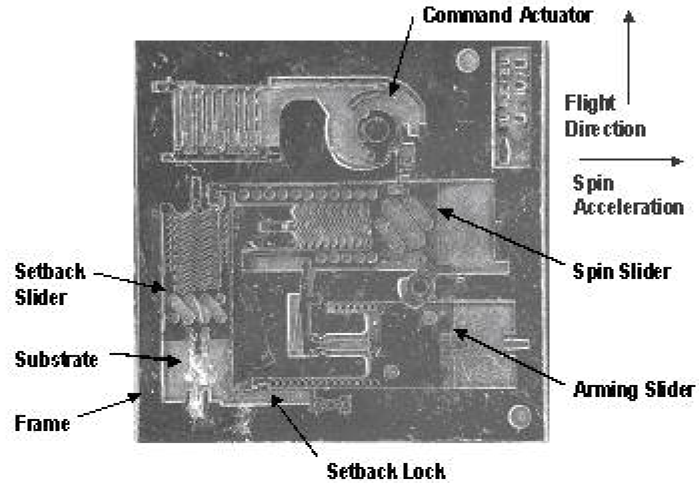

Figure 12. Updated 10x10-mm S&A geometry, pre-launch.

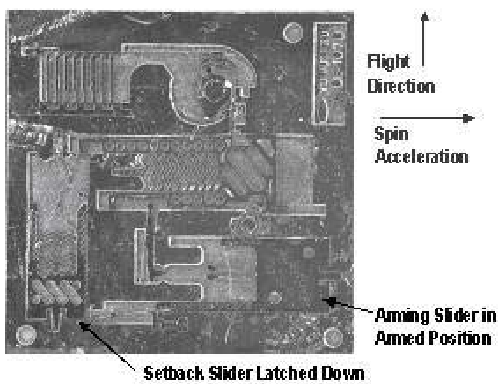

Figure 13. Updated S&A geometry, post-launch.

strong and failed to release the lever, so that the first environmental lock was never removed and the mechanism could not proceed to arm. To remedy this problem for the remaining eight units, the assemblies were opened and the shear tabs were manually removed before the shots were made. However, these three shots were valuable to illustrate that if the setback lock is not removed, the arming slider remains locked in the safe position.

The cause of the one arming failure is not known, except the probability is that there was some dust fouling of the device. This risk was real because to remove the shear tab on eight MEMS S&A assemblies mentioned above we had to perform unexpected 'surgery' on them in a dusty tool shed using a screwdriver and a rusted razor knife!

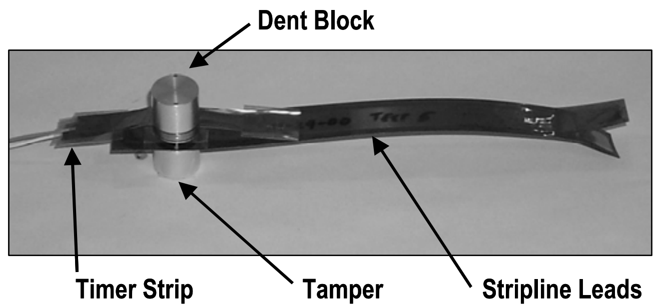

Figure 14. Fixture for MSF test and demonstration.

7.2 Gun Firing in a 20-mm Grenade (OICW)

On 17 April 2002 ten more prototype MEMS-based mechanical S&A assemblies were demonstrated using 20-mm inert HEAB rounds fired from a fixed barrel with recoil (Mann barrel). The test was performed at the Alliant Techsystems Proving Ground at Elk River, MN. Five of the rounds were fired at the nominal system loading of 231 m/s muzzle velocity (about 45,000 peak Gs) and 490 rps spinrate, traveling 300-m into a soft catch target of fiberboard panels. Five more rounds were fired with an increased propellant loading to achieve 65,000 Gs peak acceleration, to provide a 40% overtest. Of the ten rounds shot at both speeds, nine armed successfully. The remaining round, which did not arm, demonstrated that when safety locks are not removed, the arming slider remains locked in the safe position. Inspection of the fired units revealed that no breakage or damage occurred in the MEMS assemblies, even with the 40% overtest of the fast rounds, and even when one of the fast rounds overshot the target, tumbled on the ground, and came finally to rest in a sand pile 500-m downrange. Furthermore, all the spring and slider latches stayed latched as designed. The test results are summarized in Table 1.

Table 1. Results from 20-mm Ballistic Test

Shot	S&A Chip Size (mm)	Peak Accel, Gs	Muzzle Speed, m/s	Arming Status
1	12 x 15	65	245	armed
2	10 x 10	65	248	armed
3	12 x 15	65	248	armed
4	10 x 10	65	247	not armed
5	10 x 10	45	222	armed
6	10 x 10	45	219	armed
7	10 x 10	45	224	armed
8	10 x 10	65	246	armed
9	12 x 15	45	220	armed
10	12 x 15	45	219	armed

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SUMMARY

A MEMS-based fuze S&A for a gun-launched 20-mm airburst grenade has been developed and partially demonstrated in the laboratory and in 20-mm and 40-mm gun firings. A compatible micro-scale firetrain has been demonstrated in the laboratory. The ballistic tests successfully demonstrated inertially-driven mechanical safety logic implemented on a micro-fabricated die measuring 10x10-mm. Two high-aspect-ratio MEMS fabrication technologies were tried in this proof-of-principle effort, with test results favoring the metal fabrication possible with LIGA, a microscale molding and electroplating technique, over the silicon fabrication DRIE process. Aspects of the development that remain to be demonstrated include a MEMS-based command actuator, full-up explosive round, and low-cost replication techniques that will make the fuze application affordable.