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2. Background

Since S&A devices are in most cases subcomponents of fuzes, the fundamentals of fuze operation and general design considerations are briefly discussed below. Additionally, the types of environmental forces typically encountered in munitions items and their relative magnitudes will be presented. Finally, several MEMS-based S&A devices currently being investigated will be summarized.

2.1 Fuze Fundamentals

The fuze's role is to make decisions for the munition that provide for: 1) *safety*, by separating the detonator from other elements in the explosive train until after separation activities, 2) *arming*, which includes sensing the environment(s) associated with intentional separation, aligning explosive trains (or removing a barrier), and preparing the munition for functioning (i.e., closing switches or logic links), and 3) *initiation* at the desired point in space or time [1]. This thesis will only focus on the first two functions – safety and arming. Also, note that “separation”, as used in this document, can mean both launch from an airframe, or firing from a rifle or tube. In most cases, launch will be used instead of separation, but ultimately the type of munition being described will determine the correct terminology.

Fuze functioning can also be described in terms of its explosive train, which begins with an initiating stimulus and proceeds through the explosive amplification stages to the detonation of the main charge of the munition. Amplification is required to convert a small, insensitive initial energy impulse into sufficient energy to detonate the

main charge in a reliable and controllable manner that also satisfies safety requirements [1]. As shown in Figure 1-2, the explosive train is a sequence of explosive elements arranged in an order of increasing output energy and decreasing sensitivity.

Some important considerations that must go into a fuze design are safety, reliability, producibility, lifecycle costs, and standardization. Standardization has the overall effect of reducing development time, lowering costs, and decreasing manpower requirements [1]. Managing these considerations is a challenge for the fuze designer when selecting a design approach to satisfy mission requirements due to the large variety of munition types that exist in most stockpiles. Different munitions usually have unique fuzing requirements based upon their intended use environment and physical size. A list of munition types could include mines, grenades, projectiles, pyrotechnics, rockets, missile warheads, and artillery/tank/mortar ammunition [1]. This is only a partial list; however, it is obvious that a large assortment of fuzes is needed to accommodate these varying munitions. Clearly, the range of munition requirements and associated performance parameters complicates fuze standardization.

2.2 Environmental Factors in Fuze Design

To ensure safety and reliably control arming, it is critical to fully understand the environments and associated stresses that a fuze will encounter during its entire lifetime, or its “factory-to-function sequence” [1]. S&A devices have to be designed to function flawlessly under these varying conditions. These environments can be characterized as either natural or induced, depending on the source of generation. Environments independent of human interaction are considered natural environments, and include temperature, pressure, humidity, rain, hail, dust, and salinity. Environments that are

generated from human-made equipment or munitions are considered induced environments, and include acceleration, spin, dynamic air pressure (ram air), thermodynamic heating, vibration, drag, creep, and target impact [1].

All of the munition types mentioned in the previous section will be subjected to most of these environments, either during its storage lifetime or its flight/launch lifetime. Consequently, the fuzes and S&A devices that are designed for these munitions will also be exposed to these environments. Furthermore, while each munition type will generally be exposed to similar environments during storage, handling, and maintenance, the environments during launch will be dramatically different depending on the physical dimensions of the munition and its method of separation, i.e., rocket-propelled launch, cartridge fired, or separation due to gravity. In other words, a large missile fired from an aircraft will experience forces much different than a small rotating projectile fired from an automatic cannon, or a bomb dropped from an aircraft. As a result of the conflicting environments exposed to different munition types, a large and diverse group of fuzes and S&A devices must be designed to take advantage of the “most predictable and consistent” environmental forces available for a particular type of munition and its application [1].

Clearly, environments such as temperature, vibration, shock, and humidity must be tolerated by all fuzes so that safety is maintained and future functioning is not degraded [1]. In addition, at least two independent environmental conditions must be sensed in order to ensure an intentional launch has occurred and prevent unintentional arming [2]. Some common environments used to operate S&A mechanisms and arm munitions are acceleration (to include both setback and angular), deceleration (creep or

drag), rotational velocity (centrifugal force), ram air pressure, hydrostatic pressure, aerodynamic heating, and gravity [1]. The range and magnitudes of forces for the typical munition categories are listed in Table 2-1.

As can be seen from the table, projectiles experience forces greater than any other type of munition. Both acceleration and spin are the environments most commonly used to induce arming in projectile fuzes because they are reasonably predictable. Likewise, launched grenades generate acceleration and spin forces of sufficient magnitude to perform the arming function (the values listed in Table 2-1 are for the 40-mm grenade) [1]. However, the spin rate for missiles and rockets is not usually large enough to trigger the arming mechanisms. Therefore, missile fuzes typically use acceleration for at least

Table 2-1. Typical Forces During Launch and Free Flight [1].

*	PROJECTILE		ROCKET	MISSILE	LAUNCHED GRENADE	MORTAR
	Small Caliber	Large Caliber				
Acceleration (Setback), [g]	71 – 125 $\times 10^3$	2.5 – 60 $\times 10^3$	40 – 6500	12 – 40	18 – 65 $\times 10^3$	0.3 – 10 $\times 10^3$
Spin, [rps]	1917 – 2030	45 – 500	0 – 50	3 – 12	63 – 200	10 – 50
Spin, [rpm]	115 – 122 $\times 10^3$	2.7 – 30 $\times 10^3$	0 – 3 $\times 10^3$	180 – 720	3.78 – 12 $\times 10^3$	0.6 – 3 $\times 10^3$
Velocity, [m/s]	825 – 1080	610 – 1173	514 – 1116	96 – supersonic	76 – 366	242 – 320
Velocity, [Mach]	2.42 – 3.17	1.79 – 3.45	1.51 – 3.28	.028 +	0.22 – 1.08	0.71 – 0.94
Deceleration (Creep), [g]	> 10	3 – 32	3	n/a	n/a	< 1
Aerodynamic Heating, [K]	753	673	698	negligible +	negligible	negligible

* g – acceleration due to gravity (1 g = 9.8 m/s at sea level); rps – revolutions per second; rpm – revolutions per minute

one environmental energy source with the other independent source usually coming from onboard batteries used to power secondary locks for out-of-line mechanisms. Rocket fuzes encounter similar environments as missile fuzes, except that their launch acceleration is usually higher. Also, newer versions of rocket fuzes have made use of ram air as an energy source to supply electrical power for arming devices [1].

For other munitions, like mortars, the use of spin as an arming environment largely depends on the launch method. For example, 60-mm and 81-mm caliber mortars are launched from smooth-bored tubes, which do not induce spin on the projectile. The predominant environmental forces for these mortars are acceleration and ram air. On the other hand, the larger 4.2-in. (~ 107 mm) caliber mortar is launched from a rifled barrel, which does induce spin on the round, and the resulting centrifugal force, along with the induced acceleration force, provides enough energy to arm the fuze [1].

Other munition types not listed in Table 2-1 are scatterable mines and submunitions. These munitions are capable of being fired from a 155-mm howitzer projectile or dropped from an aircraft. Environments used for arming these types of fuzes are acceleration, spin, and ram air. For comparison purposes, the Ground Emplaced Mine Scattering System used by the Army and the CBU-24/B Cluster Bomb (BLU-26/B submunition) used by the Air Force have spin rates of approximately 53 revolutions per second (rps) and 45 rps, respectively [1].

2.3 Current Research Efforts on MEMS-Based Safe and Arm Devices

Various government agencies have been actively studying S&A devices that have been designed and fabricated using MEMS techniques in order to capitalize on the reliability, repeatability, and economic benefits that come from microelectronic

fabrication. Moreover, MEMS S&A devices have the potential to revolutionize the design of munition systems that are currently limited due to physical constraints imposed on them by individual component dimensions. In the following paragraphs, the research that these agencies have been performing on micro-scale S&A devices is examined. To begin with, the work being done by two of the U. S. Navy's warfare centers is discussed. Next, a device being developed by Sandia National Laboratories, followed by the micro-scale S&A efforts of the U. S. Army is presented. Lastly, the U.S. Air Force's approach to miniaturizing munition components will be reviewed.

2.3.1 Naval Surface Warfare Center – Indian Head Division

The Naval Surface Warfare Center (NSWC) is part of the Naval Sea Systems Command, which is the primary activity for designing, engineering, integrating, building, and procuring U.S. Navy ships and their associated combat systems [3]. Their Indian Head Division, which develops explosives and propellants for use in state-of-the-art weapons systems [4], has been investigating MEMS-based S&A devices for over a decade. One of their objectives is to provide a “smarter” device that increases reliability and safety, while simultaneously improving accuracy [5], [6]. A majority of their efforts have concentrated on the development of an S&A for the Canistered Countermeasure Anti-Torpedo (CCAT) program [6]–[8].

The size advantage to using MEMS technology is readily apparent when one considers that firing devices for Navy torpedoes have decreased in volume by 87% (from 118 in.³ to 15 in.³) since the 1970's [7]. Figure 2-1 shows the relative size of the S&A die in comparison to other CCAT warhead components. The outer diameter of the CCAT is 6.75 in. and the package that contains the actual S&A die is less than 1 in.³. Although

not depicted in the figure, the firing device contains three additional MEMS components. One is an acceleration sensor that senses the g-forces due to an actual launch, and the other two are an internal measurement unit and a flow sensor used to ensure safe separation from the launching platform [8].

Functional Description

The fundamental concept for their S&A device is the interruption of optical energy required to charge a photocell that ultimately produces the high voltage output

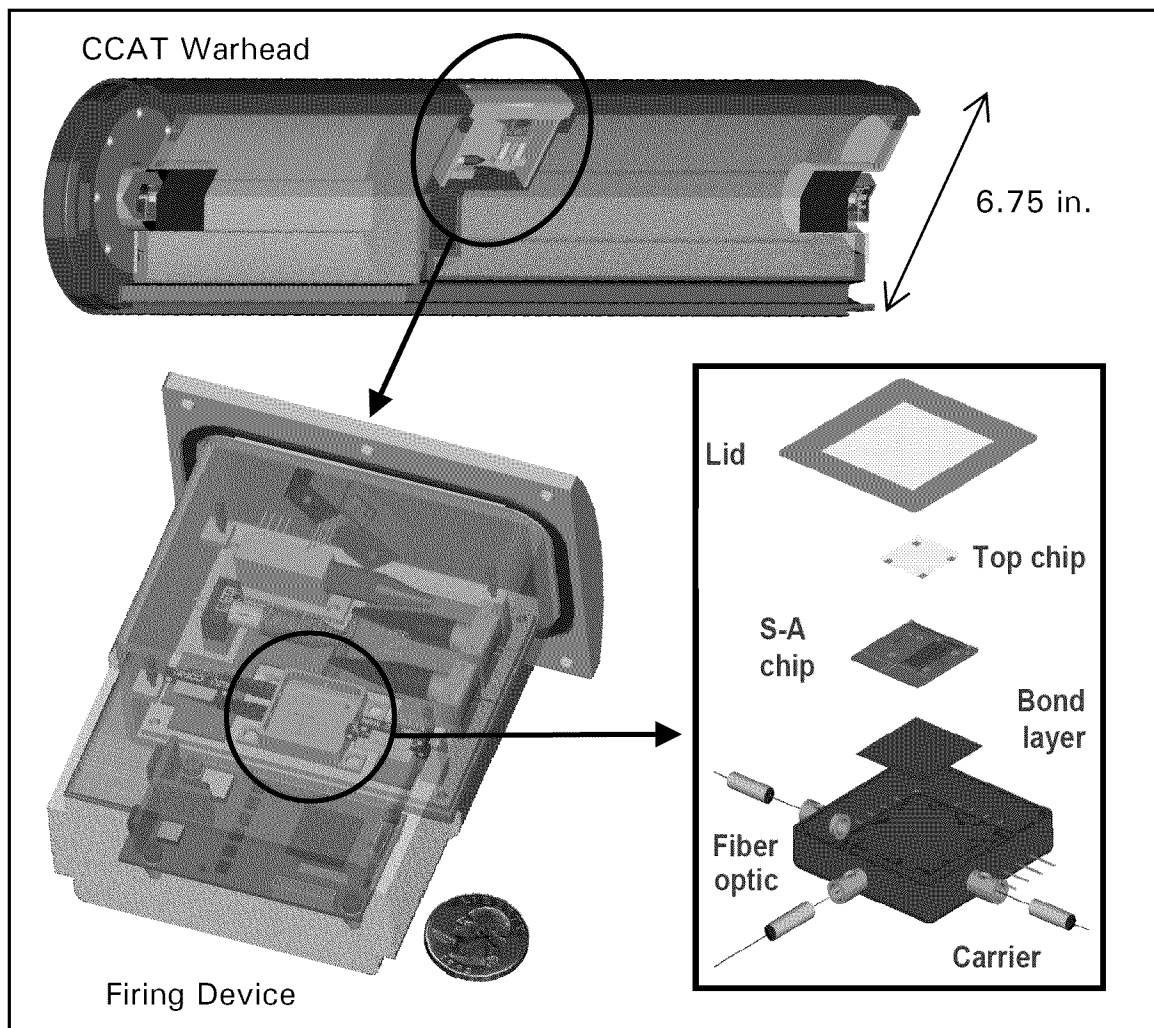


Figure 2-1. Relative size comparison between CCAT warhead, firing device, and MEMS-based S&A device [7], [8]. Warhead outer diameter is 6.75 in. and the entire S&A package is approximately 1 in.³.

that is used to initiate the detonators [9]. Two fiber optic cables (a source fiber and a receiver fiber) are used to propagate the optical energy. The MEMS-based interrupter ensures safety by decoupling the energy from the source fiber to the receiver fiber.

Three different MEMS-based approaches to designing an interrupting/coupling actuator for the optical energy were considered. These preliminary designs were fabricated using a LIGA process where nickel was used as the reflecting material. (LIGA is a German acronym for lithographie, galvanoförmung, and abformung, which means lithography, electroplating, and molding. This process is capable of producing high-aspect ratio metallic structures with very smooth sidewalls [10]). The chosen design concept consists of a 45° edge reflector fabricated on a MEMS-based actuator that reflects the optical energy in the source fiber into the receiver fiber. This approach offers a relatively simple actuator design with a measured optical efficiency of almost 80% [9].

Figure 2-2 shows a schematic diagram of the edge reflector concept. When the edge reflector is misaligned in relation with the source fiber, the optical energy is effectively interrupted from continuing along its intended path. Conversely, when the arming command is initiated, a comb drive actuator is used to align the edge reflector with the source fiber and thus allow the transmission of energy to the receiver fiber.

More recently, the NSWC moved to a Deep Reactive Ion Etching (DRIE) process that has seen improvements in performance and a lower cost per unit [7]. DRIE uses a high-density plasma source to repeatedly etch silicon resulting in very high-aspect ratio structures [10]. One of the drawbacks with this process is the sidewall roughness that occurs on the edge reflector as a result of the scalloping effects produced during the DRIE process. This surface roughness produces a less than ideal reflectivity, resulting in

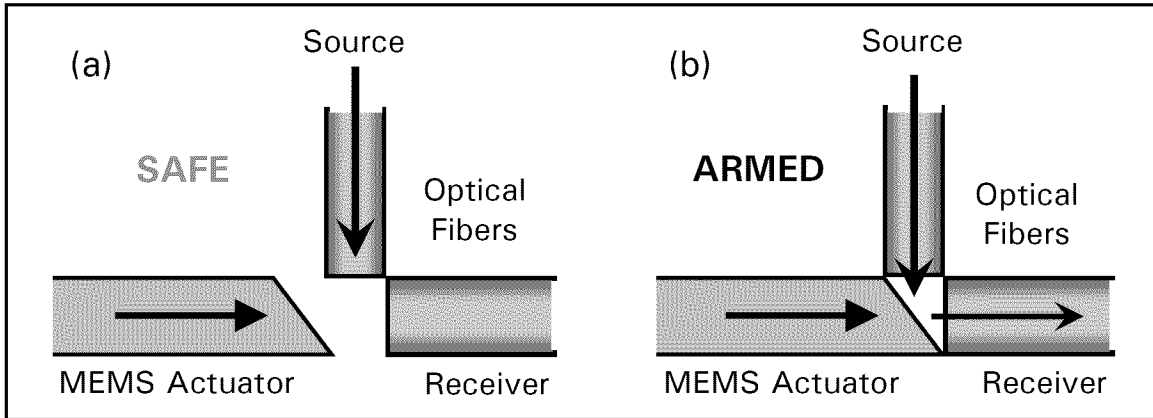


Figure 2-2. Design concept of the 45° edge reflector as an optical switch in both the (a) safe and (b) armed position [11].

an average measured optical efficiency of about 53.7%, which is approximately 10% less than the average calculated efficiency. Nevertheless, the excess energy absorbed by the reflector did not result in device failure due to structural melting. A laser diode with an emission wavelength of 810 nm and an output power of 1000 mW was used for these measurements [11].

Figure 2-3(a) depicts the comb drive actuator used to move the edge reflector surface in-line with the source fiber, along with the approximate device dimensions in millimeters. Figure 2-3(b) is a scanning electron microscope (SEM) image that shows the fabricated comb drive actuator. Figure 2-4 shows an SEM image of the edge reflector in relation to the source and receiver fibers used in this device. Note the thickness of the reflector is approximately 100 μm . The comb drive actuator was shown to be capable of moving the reflector 200 μm with a drive signal of 50 VDC [11].

NSWC Conclusion

The successful results of the NSWC efforts have facilitated progress for the CCAT acquisition program, which is scheduled to enter Low Rate Initial Production in

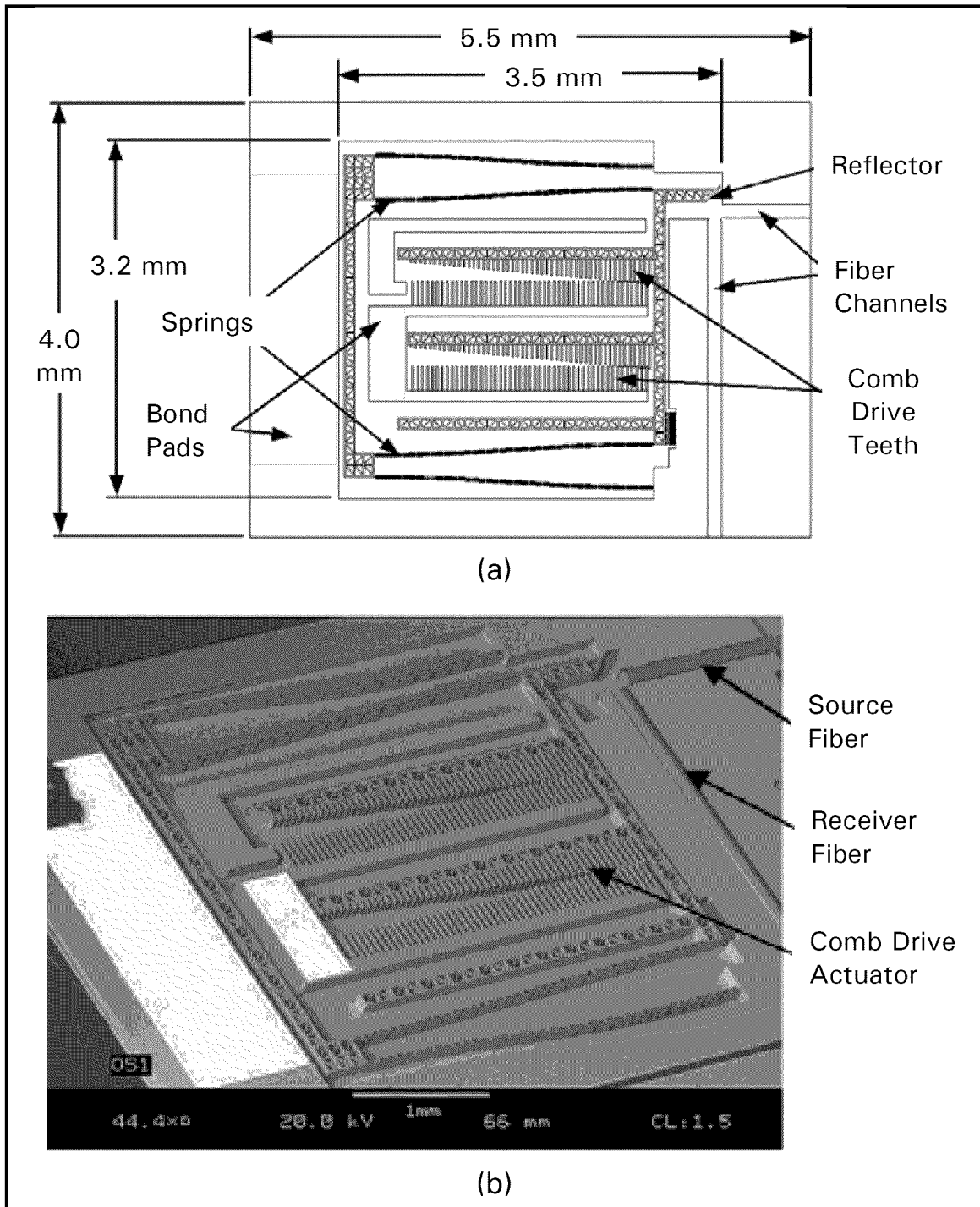


Figure 2-3. (a) Schematic of comb drive actuator used to align the edge reflector with the source fiber. (b) SEM image of fabricated comb drive actuator along with both the source and receiver optical fibers [11].

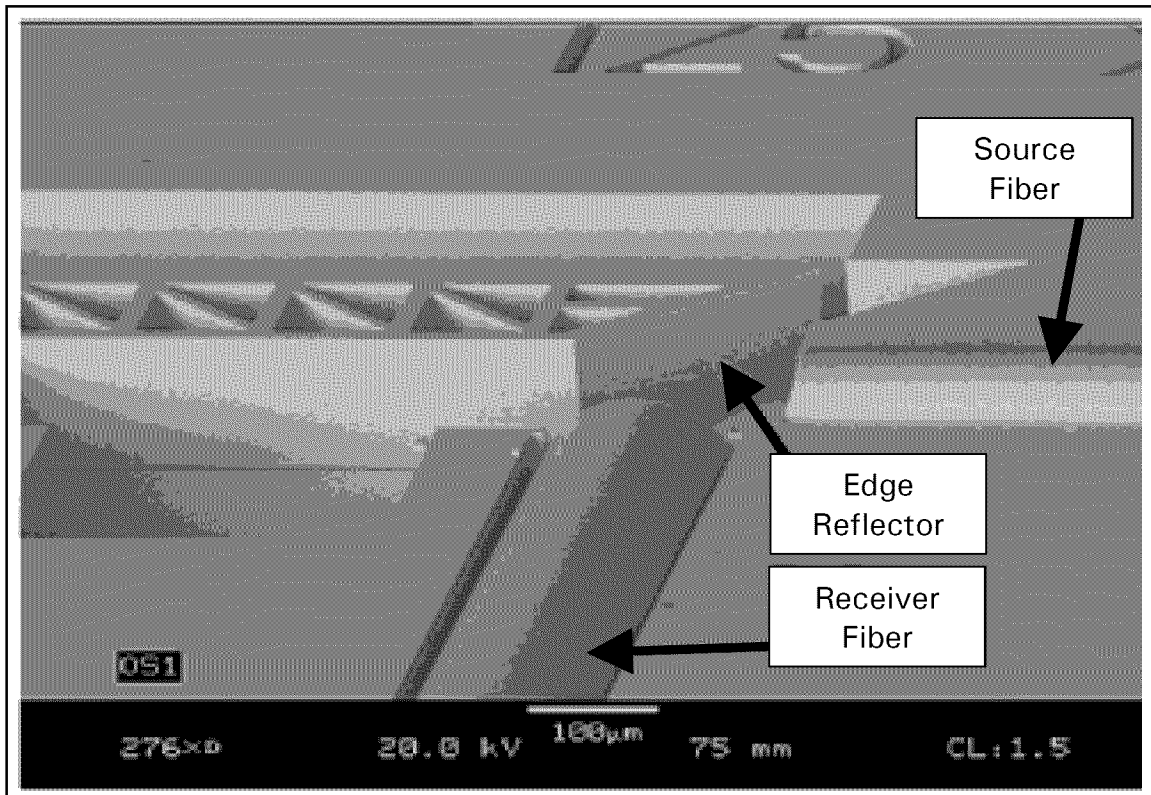


Figure 2-4. SEM image of the source and receiver fiber alignment with the gold-coated silicon reflector. The thickness of the reflector is approximately 100 μm [11].

fiscal year (FY) 2008 [12]. Their research has also enabled the development of a MEMS S&A for a shipboard submunition that senses arming environments and will eventually be capable of integration with novel energetic materials at low cost. This submunition S&A is designed to use an out-of-line microdetonator ($< 300\text{-}\mu\text{m}$ thick) that requires less explosive material than conventional detonators, by about two orders of magnitude [8]. Finally, the work of the NSWC has enabled the possibility for a new generation of Navy underwater weapon systems that maintain safety and ensure arming through the use of MEMS-based S&A devices [6].

2.3.2 Naval Air Warfare Center – Weapons Division

The Naval Air Warfare Center (NAWC) is part of the Naval Air Systems Command, which is the primary activity for developing, testing, and managing “technologically superior” airborne weapon systems [13]. Their Weapons Division has been investigating a distributed S&A system that uses an arming control unit to generate unique arming commands to selected microdetonators in the system. The arming control unit interprets the environmental conditions received from the MEMS sensors prior to generating the arming commands. Each “smart” detonator in their distributed system incorporates an electromagnetically actuated MEMS slider mechanism, microelectronics, and miniaturized explosive components [8], [14]. Figure 2-5 shows the exploded view of the distributed S&A system for a conceptual warhead.

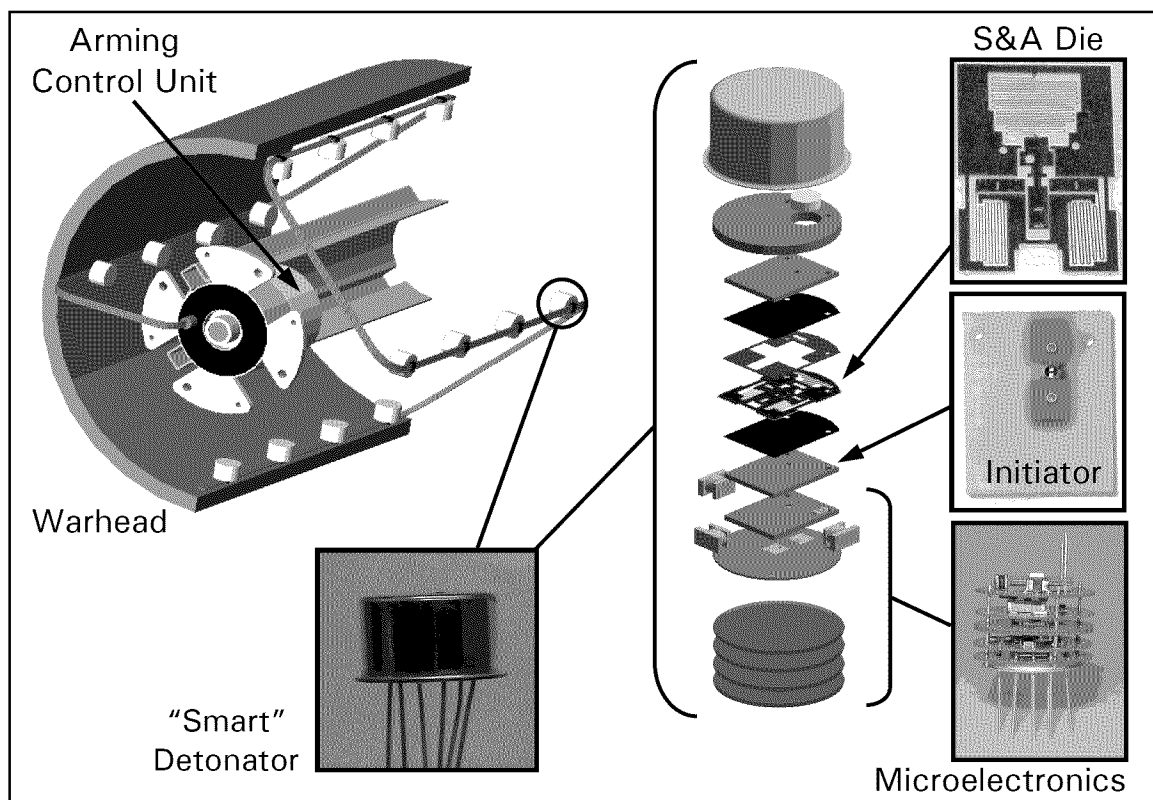


Figure 2-5. Exploded view of the distributed S&A system in a conceptual warhead application. Diameter of “smart” detonator package is 13 mm [15].

Functional Description

The S&A function is performed by a spring-loaded slider mechanism with an attached explosive primer. In the safe position, this primer is physically separated from the follow-on explosive components to ensure an interrupted explosive train. The slider is locked in the safe position by two spring-loaded latch mechanisms that are disengaged by miniature electromagnets when the proper signal is received from the arming control unit. In this unlatched (armed) condition, the slider is free to move the primer in-line with both the detonator and the follow-on explosive charges to allow a continuous explosive train. The slider mechanism moves because of a pre-loaded spring flexure that pushes the slider when the latches are disengaged [14]. An operational schematic of the MEMS slider along with an image of the actual device is shown in Figure 2-6.

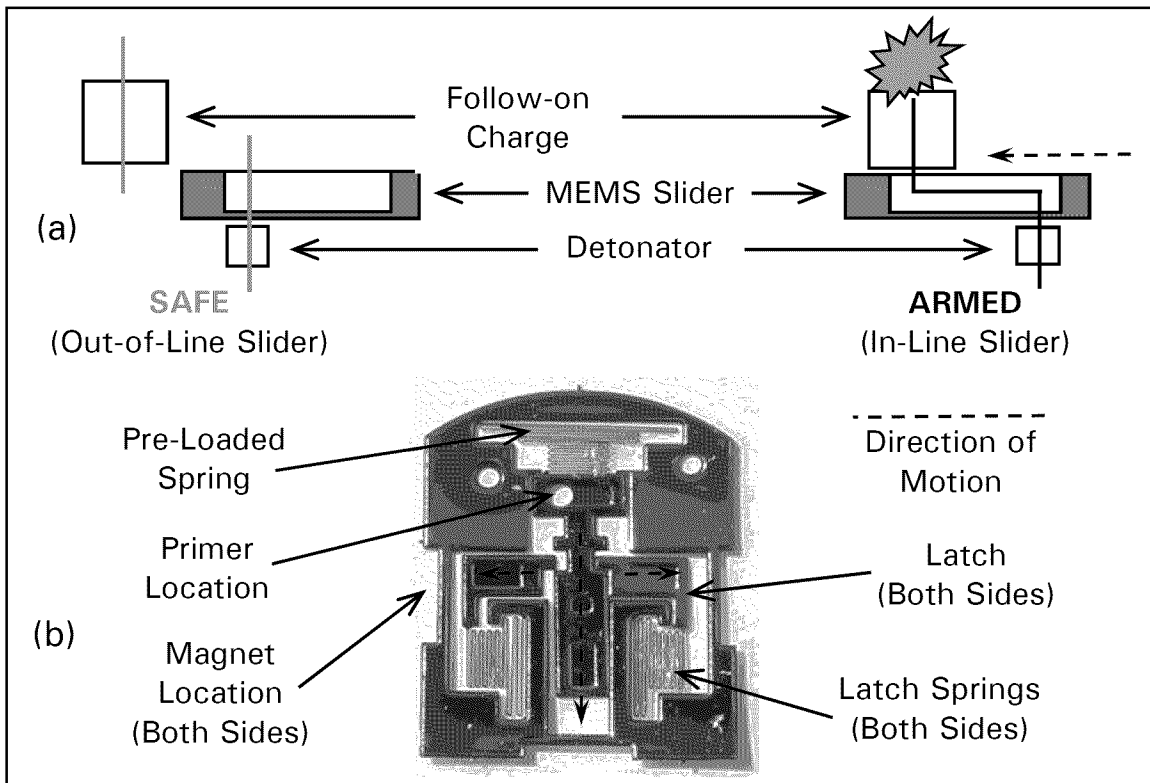


Figure 2-6. (a) Schematic diagram of slider mechanism. (b) MEMS slider mechanism shown with significant components labeled [14].

One of the benefits of this design is that it gives the warhead some performance capability by allowing the arming control unit to determine the most advantageous way to initiate the distributed system of detonators. For example, a line of detonators or a staged sequence of detonators could be initiated in order to direct the detonation energy of the warhead in a specific direction. This allows for increased flexibility and opens up additional design possibilities for future generation weapons [14]. A diagram of different initiation schemes is shown in Figure 2-7.

NAWC Conclusion

Major accomplishments of the NAWC “smart” detonator program include a successful demonstration of the safety provided by the out-of-line primer and energy transfer of small in-line charges using the MEMS-based slider mechanism. Additionally, the sequential firing of multiple detonators has been shown. This program has smoothed the progress for other integrated MEMS and microelectronic S&A devices that are significantly smaller than what can be provided by current technologies [8]. Clearly, the capability to produce miniaturized “smart” detonators by integrating MEMS actuators, microelectronics, and micro-explosive components will assist other designers of micro-scale S&A devices to facilitate future weapon concepts and applications.

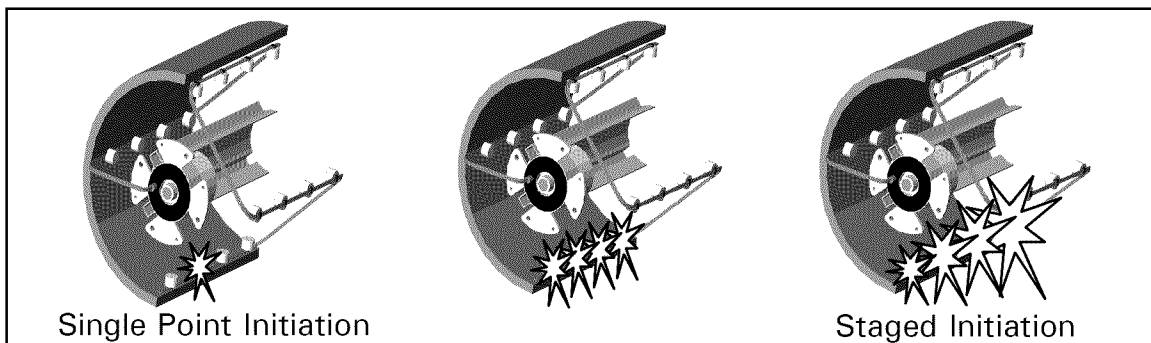


Figure 2-7. Different detonator initiation schemes provides for a potential aiming capability by directing the blast of the warhead [14].

2.3.3 Armament Research, Development and Engineering Center

The Armament Research, Development and Engineering Center (ARDEC) is the U. S. Army's principal activity responsible for the development and sustainment of current and future armament technologies [16]. Recently, their Fuze Division, which is part of the Fuze and Precision Armaments Technology Directorate, has been extensively characterizing a MEMS-based S&A device for incorporation into high-explosive air-burst munitions [17]. The robustness of their device has been proven from the demonstrations that have been performed to date. Currently, they are leveraging off the success of this device to facilitate improved producibility of MEMS-based S&A devices for advanced munitions. The success of these efforts will allow this technology to become more affordable and enable a high-volume manufacturing capability advantage for commercial companies [18].

Functional Description

ARDEC's S&A device uses several slider mechanisms that operate as environmental sensors for the acceleration and spin forces generated after separation from the gun barrel. For safety, the device maintains a transfer charge out-of-line from in-between the detonator and lead charges of the fuze. The arming slider's out-of-line and in-line (armed) positions are controlled by mechanical locks, which are disengaged by two independent environmental forces. See Figure 2-8 and Figure 2-9 for a schematic of the S&A device in both the safe and armed positions, respectively. Initially, the linear acceleration due to launch is encountered, which causes a setback slider to move against a spring-tensioned load. If the proper amount of acceleration is sensed (indicating a valid launch), a safety lock lever on the arming slider is disengaged. Next, the centrifugal

force, resulting from the spin of the projectile, forces the arming slider to move against its pre-loaded spring. This action places the transfer charge in-line with the other explosive components; thereby completing the explosive train. An additional safety feature on this S&A die is a command slider that prevents the arming slider from moving into a fully armed position unless independently enabled by high-pressure propellant gases when the weapon is committed to launch. This method to actuate the command slider is notional and it may eventually be actuated by other means. Two main advantages for this S&A device is its simplicity and the fact that it does not rely on any external environmental sensors [19].

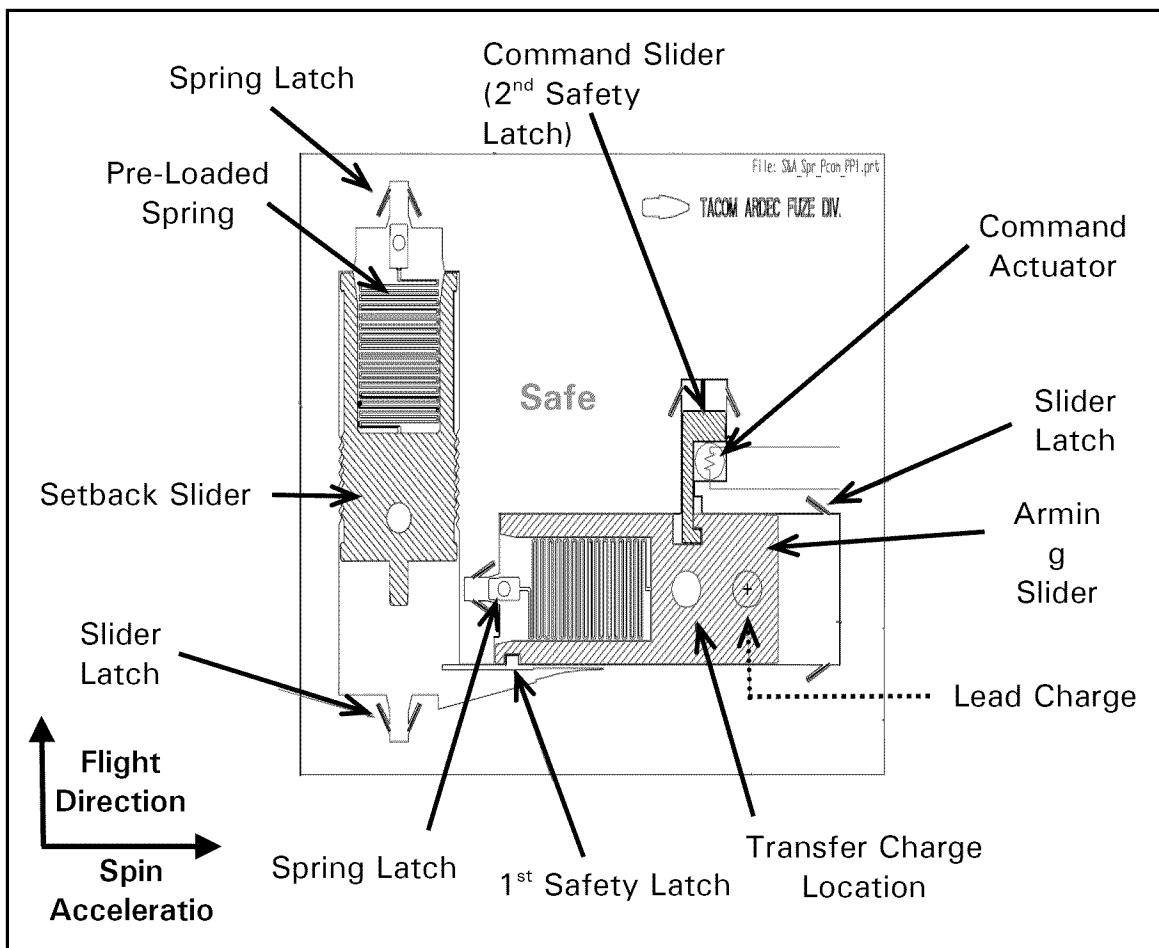


Figure 2-8. Operational schematic of the ARDEC S&A device in the safe position [19].

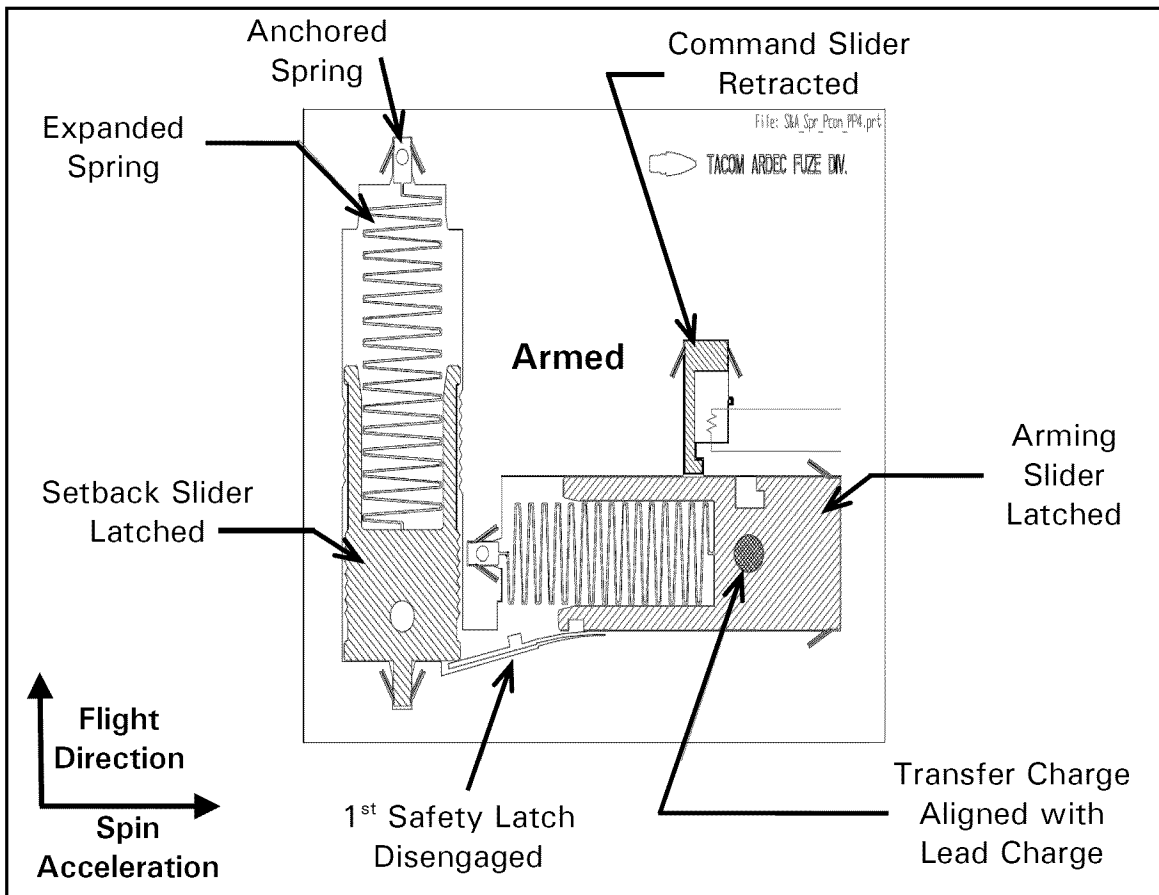


Figure 2-9. Operational schematic of the ARDEC S&A device in the armed position [19].

ARDEC Conclusion

Follow-on steps for ARDEC's MEMS-based S&A device include continued research into end-to-end manufacturing objectives and successful integration into current weapon systems. In FY 2008, this device is scheduled to be incorporated into two existing acquisition programs that will be entering Low Rate Initial Production [17]. Noticeable benefits of this device are increased safety for the warfighter, while simultaneously improving lethality by enabling an increased warhead size due to smaller mechanical and electrical components. Additionally, smaller components contribute to the overall reduction of logistic burdens, as well as a decrease in the carrying load for individual soldiers [18]. Finally, the reduction in cost, resulting from the volume

production offered by MEMS technology, ultimately facilitates commercial interest in manufacturing these devices and serves to advance the development of state-of-the-art MEMS S&A devices.

2.3.4 Air Force Research Laboratory – Munitions Directorate

The Air Force Research Laboratory – Munitions Directorate (AFRL/MN), is the U. S. Air Force organization responsible for developing conventional munitions technologies [20]. The Fuze Branch of its Ordnance Division is using MEMS technology in the development of an accelerometer suitable for use in the harsh environments typically encountered by penetrator-type weapons just prior to fuze initiation. In an effort to understand the material properties required to operate in these high-stress, high-shock, and high-temperature environments, AFRL/MN has been investigating the stress development and fundamental failure mechanisms of thin-film silicon carbide (SiC) structures [21]. Data collected from these tests will enable better characterizations of device failure modes and be used to improve future devices.

SiC was selected as the sensing material due to its superior mechanical properties over other microprocessing-friendly materials. For example, the bulk modulus for SiC is more than double the value for silicon, and the thermal conductivity is more than 3.5 times that of silicon. In addition, the energy bandgap for SiC is twice the bandgap for silicon at 300 K [21], [22]. Three types of SiC MEMS devices were designed and fabricated using Plasma Enhanced Chemical Vapor Deposition (PECVD) to deposit a thin epilayer of SiC over a bulk micromachined SiC substrate to form a suspended membrane. Piezoresistive elements were fabricated on top of the SiC membrane to measure stresses in the membrane when subjected to extreme shock conditions. Figure

2-10a depicts a cross-section of the fabricated test structure and Figure 2-10b shows the stress contour plot of the membrane under an applied shock load. Notice the location and relative magnitudes of resulting compressive and tensile stress [21].

AFRL Conclusion

This type of material research will foster improvements in the performance of next generation fuzing for munitions such as the High Speed Penetrator (HSP). A key requirement for a penetrating warhead, like the HSP, is the ability for the fuze to survive a high-speed impact into reinforced barriers and still operate properly [23]. Currently, the baseline design fuze for the HSP is a modified Multiple-Event Hard-Target Fuze (MEHTF) [24]. This fuze has shown the capability to survive loads that are comparable to those expected by impact and penetration [23]. Clearly, the investigation of exotic materials, combined with the benefits offered by MEMS technology, will enable the development of micro-scale fuzing technology that is capable of performing safety, arming and initiation functions for demanding weapons concepts like the HSP [24].

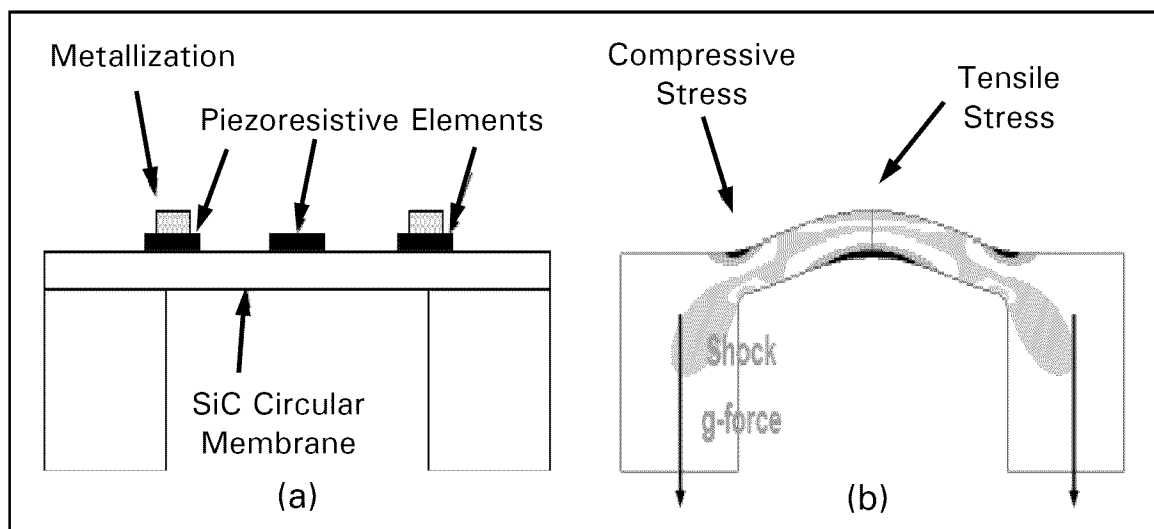


Figure 2-10. (a) Depiction of circular SiC membrane formed over a bulk etched SiC substrate. (b) Stress counter plot of a similar structure under an applied shock load [21].

2.4 Introduction of Design Concept for MEMS S&A Device

The devices discussed above introduced novel MEMS-based S&A device concepts being considered for implementation. In all these devices, the key method of ensuring safety was interruption of the explosive train in some manner. For instance, this could be accomplished by providing a physical barrier that prevents the detonator energy from reaching the lead charge or by removing an explosive component away from the detonator charge to prevent propagation of the explosive energy in the case of inadvertent initiation. Alternatively, arming was accomplished by moving a MEMS actuator in such a way as to align the necessary components to enable propagation of the detonator energy when the proper initiation signal is transmitted by the fuze. The obvious commonality between all these devices is that they are designed and fabricated using MEMS technology.

The design concept that will be discussed in the remainder of this thesis leverages on proven MEMS fabrication techniques that provide the inherent advantages of miniaturization, large volume production, reduced costs per unit, and lower parts counts. The focus of this research will be to design, fabricate, and demonstrate an interrupter mechanism consisting of an aperture that is normally closed while in the safe mode and opened when in the armed mode. It is envisioned that this interrupter would be used in concert with a microdetonator and other MEMS-based sensors to ensure the required independent environmental conditions are present prior to arming. Details of this design will be discussed in the chapters that follow.

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3. Explosive Initiation Devices and Concepts

A variety of initiator devices have been used in the past to provide the initial energy needed to begin the detonation process in an explosive train. In this chapter, some common initiating devices that have been used extensively in the past will be presented. This will be followed by a discussion of a particular initiator that has been shown to be reproducible using microelectronic fabrication techniques, and thus would be compatible with the MEMS S&A interrupter that is the focus of this thesis. In addition, a few solid-state versions of this device will be briefly presented to illustrate the various methods used to fabricate these detonators. Finally, this chapter will conclude with the description of some conceptual interruption methods and present a possible method to integrate a MEMS interrupter into a solid-state detonator in order to create a compact initiating device with a built-in S&A mechanism.

3.1 Explosive Initiation Devices

The requirement for an initiator device comes from the fact that a small impulse of energy is needed to begin the energy propagation process in an explosive train. The number of different initiators and the means in which they perform their function are large. They are often classified according to both their input energy and output characteristics. For instance, input energy usually comes from three sources: stab, percussion, or electric. Mechanical energy is used as the input energy in both stab and percussion initiators, while electric initiators use such methods as hot wire bridges or exploding bridgewires (EBW) to detonate their charge. On the other hand, output

characteristics are related to the process used to initiate follow-on explosive charges. For example, primers and squibs convert mechanical or electrical energy into explosive energy through the use of a small flame. These two devices are not generally used to initiate follow-on high explosives directly because their output energy is relatively small. However, detonators are often used to initiate follow-on high explosive (HE) charges since their output energy usually consists of an intense shock wave [1].

One common initiator device used extensively in the past is the hot wire bridge. This type of device places a high resistance wire in direct contact with a priming charge whose output energy is sufficient to initiate follow-on HE charges. When voltage is applied to the initiator, the wire bridge becomes hot enough to initiate the priming charge. Even though these devices have proven themselves reliable, they are susceptible to spurious currents that have the potential to stimulate the wire bridge. Therefore, their use is precluded in applications where safety is critical [1], [2].

Another common initiator device is the exploding bridgewire (EBW) detonator, which consists of a small bridgewire that is electrically exploded to initiate the follow-on HE charge. When a very high and very short current pulse is forced through the bridgewire, it explodes before it has a chance to melt and disrupt the circuit. This output energy has a magnitude of approximately one joule, and has been used to initiate such high explosives as pentaerythritol tetranitrate (PETN), and cyclotrimethylenetrinitramine (RDX) [1], [3]. Yet, one of the disadvantages for PETN and RDX is that they are not approved for fuze designs that use an uninterrupted explosive train. On the other hand, hexanitrostilbene (HNS) is approved for use with uninterrupted fuze designs since it is relatively insensitive to electrostatic discharge, drops, or friction, and has a large

operating temperature range (-196 °C to 200 °C) [4]. However, because of this insensitivity, HNS requires more energy to induce initiation, thus one of the main drawbacks of an EBW detonator is that it does not initiate HNS readily. The next section will discuss a newer detonator concept that is capable of detonating HE charges approved for use in uninterrupted fuze designs (e.g., HNS), and is a natural extension of the EBW detonator [1].

3.2 Exploding Foil Initiator

The exploding foil initiator (EFI) was first introduced in a 1976 report issued by Lawrence Livermore National Laboratory. In this report, the author John Stroud described “a new kind of detonator” that he informally called “the slapper” [5]. This type of detonator has several advantages over the EBW detonator. One advantage is that the exploding metal material and the follow-on explosive charge are physically separated by a thin insulating material and air gap. This contributes to safety as spurious current is eliminated as a potential for inducing detonation. Other benefits of the EFI are a reduction in input energy required for initiation and the fact that the output energy can readily detonate HNS [1].

The major components of an EFI detonator are shown in Figure 3-1. Starting from the bottom, the first component is an insulating “flyer” material that has metal foil etched on the underside. The reduced area (increased resistance) in the center of the metal foil causes vaporization of the flyer material when a high voltage is applied. The magnitude of this voltage has been reported to be in the thousands of volts for various EFI designs [5]–[7]. The middle component consists of an insulating disk that has a hole, or barrel, patterned in the center, directly above the reduced area in the metal foil. The