MICROELECTROMECHANICAL SYSTEMS (MEMS) INTERRUPTER FOR SAFE AND ARM DEVICES

THESIS

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Abstract

This thesis addresses the development of a new micro-scale interrupter mechanism for a safe and arm device used in modern weapon systems. The interrupter mechanism often consists of a physical barrier that prevents an initial source of energy, in an explosive train, from being transferred to subsequent charges. In general, when the physical barrier is removed, the weapon is considered armed, and the charge is allowed to propagate. Several issues facing current safe and arm devices systems are the shrinking industrial base for manufacturing these devices and the desire for modern safe and arm devices to be compatible with next generation weapon systems that are generally decreasing in size and increasing in complexity. The solution proposed here is to design, fabricate, and test a conceptual interrupter mechanism using Microelectromechanical Systems (MEMS) components. These components have inherent benefits over current devices, such as smaller feature sizes and lower part counts, which have the capability to improve performance and reliability. After an extensive review of existing micro-scale safe and arm devices currently being developed, a preliminary design was fabricated in a polysilicon surface micromachining process. The operating principle of this conceptual interrupter mechanism is to have MEMS actuators slide four overlapping plates away from each other to create an aperture, thus providing an unimpeded path for an initiating energy source to propagate. Operation of the fabricated MEMS interrupter mechanism was successfully demonstrated with an approximate aperture area of 1024 μm^2 being created.

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To Nicholas and Jeffrey

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MICROELECTROMECHANICAL SYSTEMS (MEMS)

INTERRUPTER FOR SAFE AND ARM DEVICES

1. Introduction

For the people that work around explosive weapons, safety is a vital concern that affects all facets of a weapon's life – from transportation, to storage, to maintenance, to buildup, to upload, to flight, and to release. The potential for a major mishap, to include both equipment and personnel, exists if a weapon is inadvertently armed during one of these operations. To ensure that the weapon is in an "armed" condition only when desired and in a "safe" condition at all other times is the function of the safe and arm device [1], which is an integral part of the weapon's fuze.

1.1 Safe and Arm Device Functional Description

The safe and arm (S&A) device is an element of the fuze, which is a critical component of all munition items. The fuze is responsible for initiating the sequence of steps that ultimately leads to weapon detonation. The method of initiation for a particular fuze depends on the intended launch environment, or the desired effect upon detonation. For example, fuzes can be designed to initiate the explosive train on impact, by sensing a relative proximity to a target, or by sensing depth of penetration through a target. This latter example applies to bunker busting-type weapons where it is desirable to penetrate through various levels of dirt and/or concrete barriers before detonation. A critical requirement for fuzes is their high reliability standards that must be maintained throughout years of storage, maintenance, and use in a variety of surroundings. For instance, fuzes and their internal components need to endure extreme environmental conditions that range anywhere from large temperature fluctuations during many years of dormant storage to the high acceleration forces experienced both prior to and in the launch environment [2], [3]. Figure 1-1 shows several pictures of fuzes currently used for both air-to-air and air-to-ground munition systems. The S&A device is a component within each of these fuzes.

The S&A device has the essential function of preventing a premature detonation by eliminating the potential for energy to reach the main charge. This is accomplished by

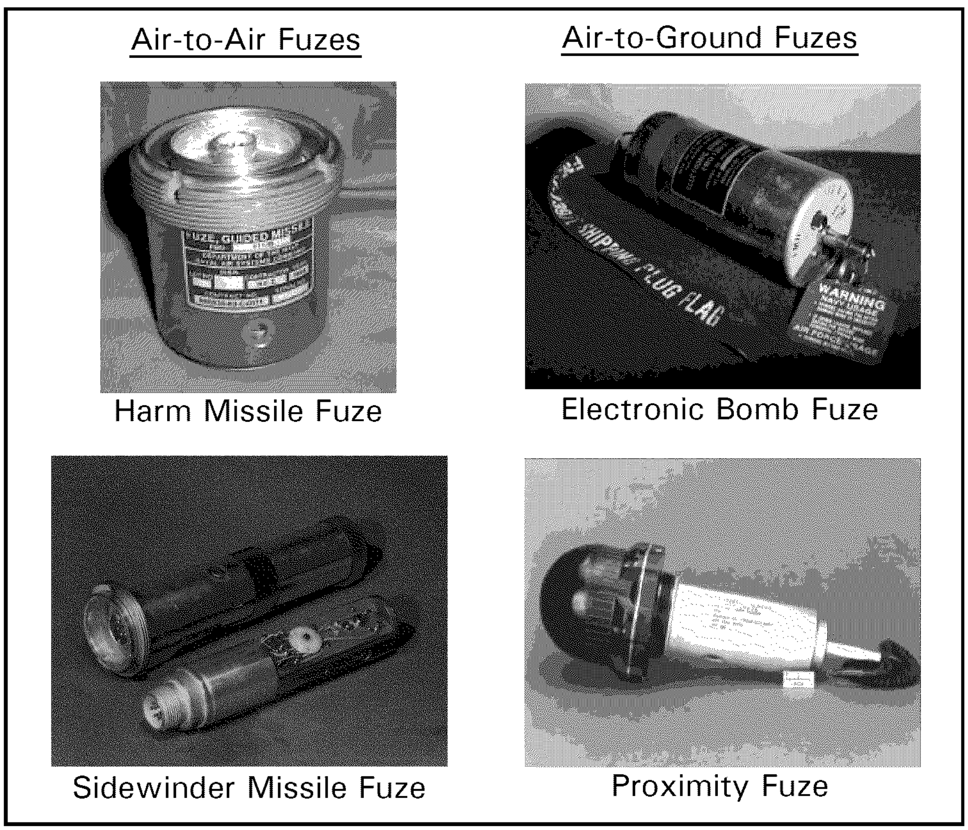

Figure 1-1. Fuzes currently being used in military weapons [4]. Safe and arm devices are a critical component within each of these fuzes.

eliminating a continuous path for the energy to propagate through the explosive train. Toward this objective, S&A devices often "interrupt" the explosive train by making use of in-line mechanisms as a way to prevent inadvertent arming. Figure 1-2 shows a schematic diagram of a generic explosive train that depicts the spatial relationship between explosive charges and the S&A device. Another function of the S&A device, equally important as preventing a continuous path, is allowing a continuous path. When a predetermined set of conditions are satisfied, the physical mechanisms (within the S&A device) that interrupt the explosive components are removed, thereby enabling the explosive energy to propagate toward the main charge, ultimately resulting in weapon detonation. In this case, an input energy source is detected by a detonator, which is a very sensitive explosive element designed to amplify a weak initial signal. The next explosive element is the lead charge, which represents the next stage of amplification. The booster charge depicts the final stage of amplification that provides the necessary explosive force to detonate the main charge [1]. To be effective, the device must remain

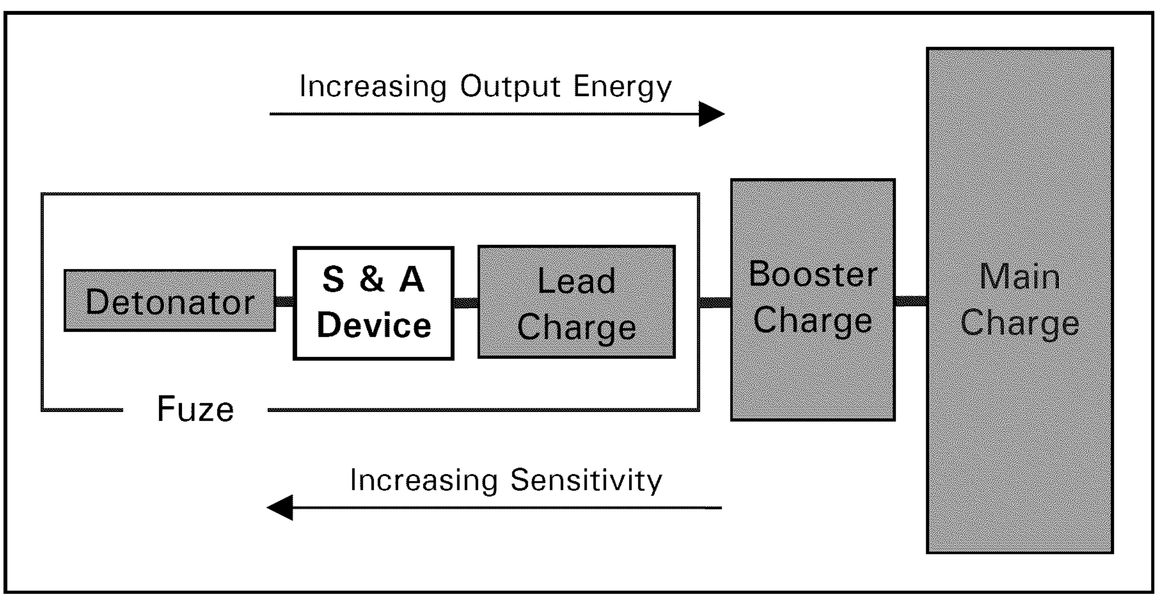

Figure 1-2. Schematic diagram of a generic explosive train. The spatial relationship between fuze, S&A device, and other charges is shown.

in a safe configuration during most of its lifetime, thus preventing an armed condition until the last possible instant. Additionally, the S&A device must be able to move very rapidly, and accurately, into the armed condition since most munitions travel at high velocities once launch has been initiated [5].

The “interruption” method used by manufacturers of S&A devices vary, but most call the mechanism that performs this function the interrupter. Interruption can be performed by misaligning the explosive components or by providing a physical barrier so that the explosive components cannot propagate through the explosive train in the case of an inadvertent initiation. Various levels of complexity can be designed into this interrupter mechanism to ensure it remains safe; however, device complexity usually has a direct impact on device reliability. More complex interrupter schemes have a greater potential to introduce single-point failure modes into the explosive train, which can result in a launched weapon that fails to detonate [6].

In order for the interrupter to move into the armed position, a specific sequence of events (for which the S&A device is designed) must be detected to ensure a valid launch command has occurred. This is typically achieved by ensuring at least two distinct environmental conditions are satisfied, which indicate an intentional detonation sequence has been initiated [7]. Care must be taken that the selected environmental stimuli will not be experienced in the munition lifecycle except when the munition is in the proper launch cycle. The launch cycle is defined as the period between when “the munition is irreversibly committed to launch” and some relatively short time after it leaves the weapon launch platform [7]. The launch platform could be an aircraft, ship, artillery tube, or rifle.

1.2 Problem Statement

One of the issues facing the munitions community in recent years is the age of fuzes and their components in existing weapons systems. The reliability of these older fuzes tend to decrease over time, and existing systems will require components to be replenished in the coming years, either through product improvement or new development programs [8], [9]. In addition to finding replacement components for older weapons systems, new S&A devices need to be developed for munitions currently being acquired. Many designs that exist today use mechanisms that were designed over two decades ago and some designs are too complex and costly with respect to other improvements being made to modern weapon systems [10]. Modern munition items tend to be designed for more reliability and accuracy, and as such require a S&A device that achieves an equal, if not better, level of performance to ensure both infallible safety and lethal functionality.

Another problem, which compounds the issue of an aging stockpile, is that old S&A designs are difficult to reproduce since the industrial base that manufactures these devices is shrinking. From 1987 to 2001, the firms that produce electronic and electromechanical fuzes shrunk by over 80 percent (from 31 to 6) [2]. Additionally, the suppliers of Army fuzes have reduced in numbers from 20 to 5 since 1999 [11]. The military downsizing that occurred in the 1990's reduced the dollars available for munitions expenditures, and as a result many manufacturers stopped producing fuzes because it became less profitable [9], [11].

1.3 Proposed Solution

A common approach in designing modern weapon systems is to miniaturize munitions, which places a 'smaller is better' requirement on all components that make up a munition item, including the S&A device. Advances in solid-state fabrication techniques have made it possible to create micrometer-scale mechanical systems, which enable alternative design possibilities for fuze designers. Consequently, S&A devices designed using micro-electro-mechanical systems (MEMS) concepts become an obvious area to explore for potential exploitation. MEMS technology is based on the thoroughly refined fabrication methods used in the integrated circuit community. The processes used in fabricating integrated circuit devices using solid-state materials have been well proven over the last 50 years. Starting with the first transistor developed in 1947 by engineers at Bell Laboratories and the first integrated circuit demonstrated in 1958 by Texas Instruments [12], tremendous advances have been made in the material research and processing technologies that enable the complex electronic devices produced today.

The attractiveness of MEMS S&A devices for modern weapons systems is their inherent benefits over current macro-scale devices. One example is that their smaller feature size offers the advantage of decreased mass, which directly benefits enhanced range and maneuverability requirements. This can be shown by considering the scale factor, S, of an object. Mass is known to scale in relation to the volume of an object, therefore, the scale factor for mass is S^3 [13]. For instance, consider a cube where the length of each edge is one meter. If each edge length is reduced to one micrometer (10^{-6} meter), the mass of the cube will decrease by $1/10^{18}$ ($S = 1/10^6$), or by a factor of 10^{18}. On a more practical scale, consider the length of each edge scaling from one millimeter

(10^{-3} meter) to one micrometer (10^{-6} meter). Applying the mass scale factor of S^3 to this example, results in the mass decreasing by a factor of 10^9.

Another example of the inherent benefits of MEMS devices is the higher fabrication volumes, which typically contributes to lower costs over time. The decrease in cost is a result of the capability to produce these devices in large volumes. This has been irrefutably witnessed in the processes used to fabricate integrated circuits, which are very similar to the processes used in MEMS fabrication. As a final example of inherent MEMS benefits, the lower part counts, that are generally characteristic of these devices, have a tendency to increase reliability over systems with a larger part count.

Clearly, if an S&A device, designed with components manufactured with MEMS techniques, could be successfully demonstrated, it would allow more design flexibility for the replenishment of fuze elements in current munitions, and enable additional approaches in the design of modern weapon systems. Additionally, MEMS-based S&A devices could be used for advanced munitions concepts, such as miniature weapons on unmanned aerial vehicles (UAV) and 'smart' bullets.

1.4 Conclusion

This research effort will focus on an interrupter design concept created completely in a MEMS fabrication process. The Multi-User MEMS Processes (MUMPs®) fabrication process was used for all four design iterations submitted as part of this thesis. Each device uses polysilicon as the structural layers and hence the specific process provided by MUMPs® is called PolyMUMPs™. The PolyMUMPs process is a three-layer, general-purpose surface micromachining process that offers two releasable polysilicon layers and one metal layer [14].

Chapter 2 of this thesis will discuss some basic concepts that must be considered when designing a munition fuze, along with the forces typically encountered in military weapons. In addition, several micro-scale S&A devices currently being investigated will be presented. Chapter 3 will discuss some common devices used to initiate explosive trains, along with a look at a specific detonator device that has been fabricated using microelectronic fabrication techniques. Chapter 3 will conclude with some ideas on how to integrate the MEMS interrupter concept proposed in this research with a microdetonator device. Chapter 4 will discuss the theory involved in designing a MEMS interrupter mechanism, and the motivation for selecting the individual components that are incorporated into the final fabricated device. Chapter 5 will discuss the test results used to characterize the performance of the individual actuation mechanisms, along with the experimental results of the fabricated S&A interrupter device. Lastly, Chapter 6 will discuss the conclusions reached based on these experimental results and present some recommendations for future work in this area.