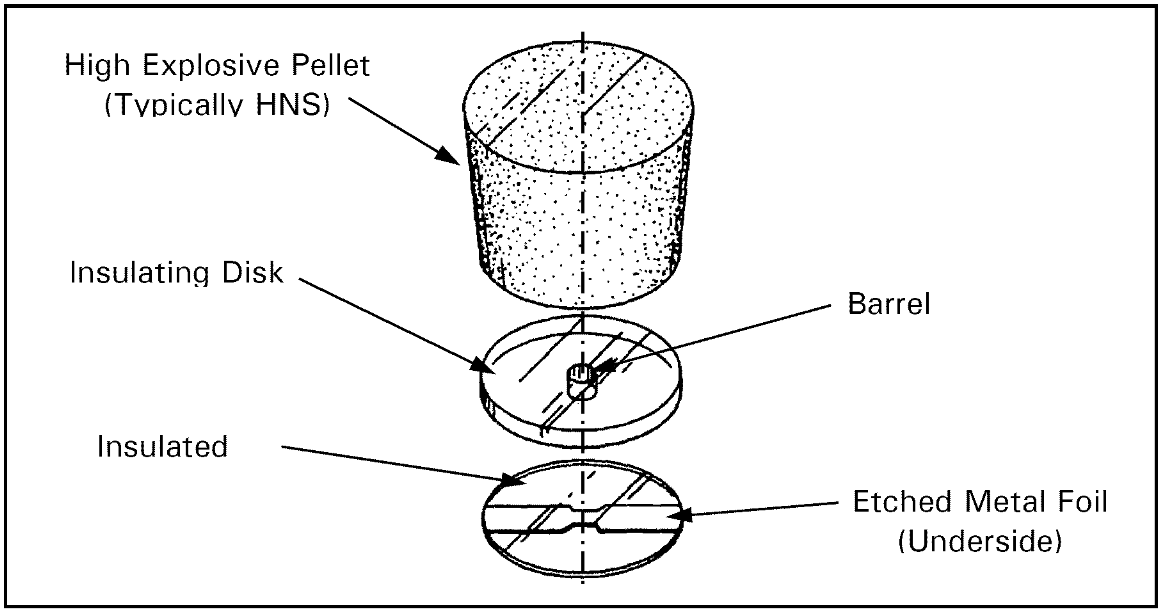

Figure 3-1. Major components used in an Exploding Foil Initiator [1].

barrel serves to shear a portion of the flyer material and acts as a channel for the detached flyer material on its way to the HE pellet. The top component in Figure 3-1 is the high density HE pellet whose output is used to begin the propagation of explosive energy to the main charge [1]. As discussed above, the explosive pellet is typically HNS, but PETN and RDX have also been used [4], [6].

The sequence of events that occur during the functioning of an EFI device is illustrated in Figure 3-2. Step 1 shows the initiator in the static condition. Step 2 shows the initiator after a high-current pulse has been applied, which vaporizes the metal foil due to the reduced area in the center. This subsequently causes the sheared flyer material to accelerate through the barrel of the insulating disk toward the HE pellet. As the flyer impacts the HE pellet, a shock wave is transmitted into the explosive material which causes detonation. From this description, it is clear why the EFI is more commonly referred to as a slapper detonator. This more familiar nomenclature will be continued throughout the remainder of this thesis.

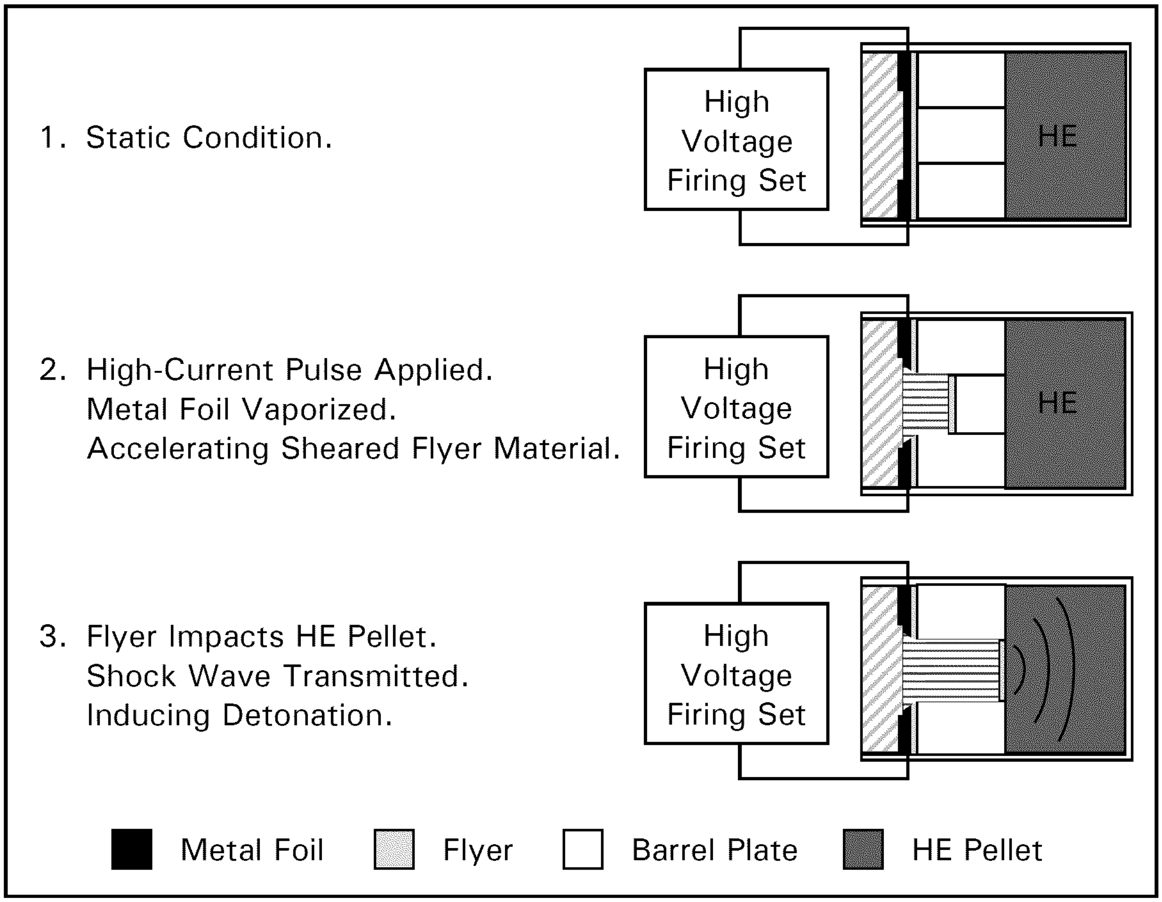

Figure 3-2. Schematic cross-section of Exploding Foil Initiator showing the sequence of steps during functioning [1].

The magnitude of the energy required to induce detonation of the HE pellet can be described in terms of the minimum kinetic energy required to induce initiation. This threshold energy is dependent on a variety of factors to include the properties of the explosive and flyer material, the volume of the flyer and the velocity of the flyer as it travels through the barrel [4], [6]. Due to the large number of factors that can contribute to the threshold energy, it is difficult to reference a single value to describe this performance parameter. However, values of 12.15 J/cm^2 and 7.0 J/cm^2 (with Mylar flyer thicknesses of 76.2 μm and 20.0 μm, respectively) have been reported as minimum energy densities for a particular manufactured lot of HNS [8]. For PETN, a kinetic energy of 19.17 mJ and 10.31 mJ can be calculated using Equation (3.1) and the reported velocities for a Kapton flyer of 3 mm/μs and 2.2 mm/μs, respectively [6], [9]. By making the assumption that the impact area is also the surface area of the flyer material, the threshold energy density can be estimated to be 15.98 J/cm^2 and 8.59 J/cm^2, which is comparable to the values reported for HNS. An exact comparison is difficult because of the diverse explosive properties (i.e., density and material surface area), the infinite possibilities for flyer material characteristics (i.e., area and density), and the chosen input current density which directly relates flyer velocity.

$$KE = \frac{1}{2}mv^2 \quad \text{(J)} \tag{3.1}$$

where

$$m = mass\ of\ the\ flyer \quad \text{(kg)}$$
$$v = velocity\ of\ the\ flyer \quad \text{(m/s)}$$

3.3 Solid-State Slapper Detonators

Since the 1980's, other EFI designs have emerged that are based on the slapper concept proposed by John Stroud in 1976. These designs are slightly modified in terms of appearance and packaging, but the functioning method remains consistent with the above description. For example, modifications have included variations in physical dimensions and material characteristics for the metal foil, flyer material, and barrel size in order to maximize the flyer output energy while minimizing the energy required to vaporize the foil. In addition, device packaging and the integration of components have been varied to increase reliability and structural integrity over long periods of time. These types of modifications include improving the quality of the foil contacts with external circuitry and barrel alignment between the flyer and HE pellet [10]–[12]. Longterm reliability is an especially important criteria for slappers used in applications that have long shelf lives, (e.g., munition fuzes). Clearly, the specific application for the slapper detonator will drive modifications in one way or another. For instance, the desired output energy of the detonator may impact the requirement for flyer velocity, which depends on the input electrical energy applied to the foil [13]. Furthermore, the applications for slapper detonators extend beyond their use for military weapons, namely, large-scale drilling and mining operations.

As recently as 1989, slapper detonators have been fabricated using microelectronic fabrication techniques [14]. These solid-state detonators bring with them the inherent benefits of large volume/low-cost production and high-reproducibility. Using this method also eliminates the precise machining, aligning, and bonding that must occur when conventional slappers are manufactured [7]. Another obvious advantage to fabricating slapper detonators using microfabrication techniques is the ease at which additional circuitry can be fabricated directly on the die. For example, the circuitry necessary to fire the slapper could be added, along with other switches or sensors required for device operation. Finally, these advantages are compatible with typical munition development objectives (i.e., reduced volume and decreased mass) [15]. In the next section, three solid-state slapper designs will be briefly discussed to show that microfabrication can provide a method for improving these already successful devices.

3.3.1 Design for Silicon-Based Slapper Detonator

In a patent issued in 1989, Nerheim et al. described a method in which slapper detonators could be fabricated using standard microelectronic fabrication techniques almost exclusively. Illustrations of the proposed silicon slapper detonator are shown in

Figure 3-3 and Figure 3-4. The process begins with an epitaxial layer of silicon grown on a typical silicon wafer. This layer eventually becomes the flyer material and is described as being grown to approximately 25-μm thick, but other thicknesses may be more appropriate depending on the application. Next, a 0.3 – 0.7 μm layer of silicon dioxide is grown on the epitaxial silicon to serve as an insulating layer. This step is followed by the deposition and patterning of the two metal contacts and a reduced center area for the vaporizing metal (foil). Alternatively, a higher density metal could be deposited in the center area in order to provide more vaporizing mass, which would increase the velocity of the flyer. This would subsequently provide an exponential increase in the kinetic energy impacting the HE pellet, as shown in Equation (3.1). Finally, the backside of the wafer is masked, and an isotropic wet etchant is used to etch completely through the silicon wafer stopping at the epitaxial grown silicon layer. This process defines the barrel and exposes the flyer for the slapper detonator [14].

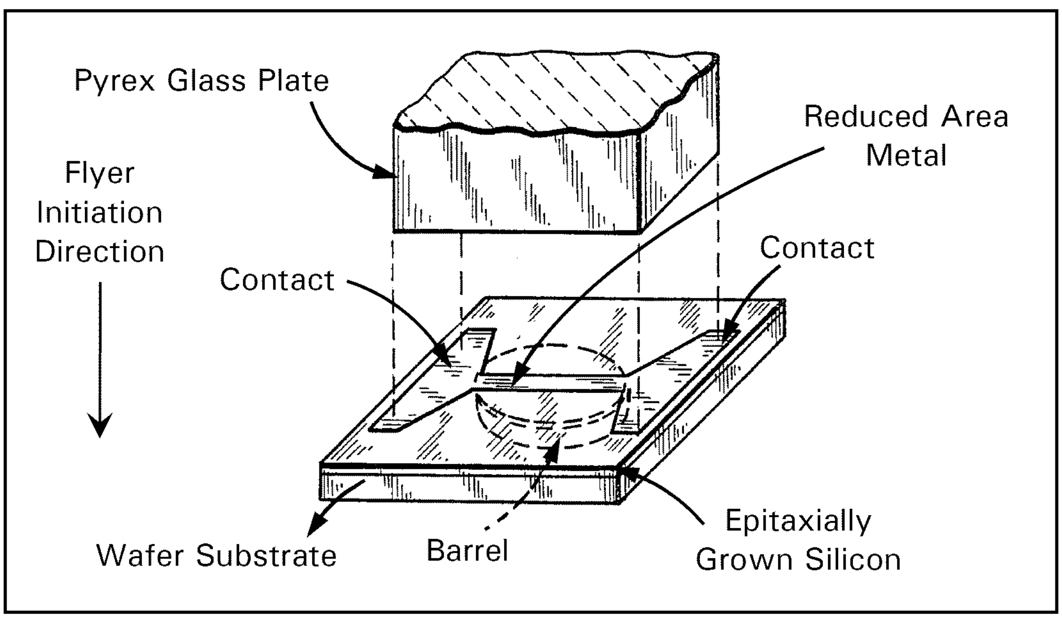

Figure 3-3. Illustration of a proposed silicon slapper detonator design [14]. All layers are deposited using microfabrication techniques, except for the Pyrex glass plate, which is epoxy, bonded during post-processing steps.

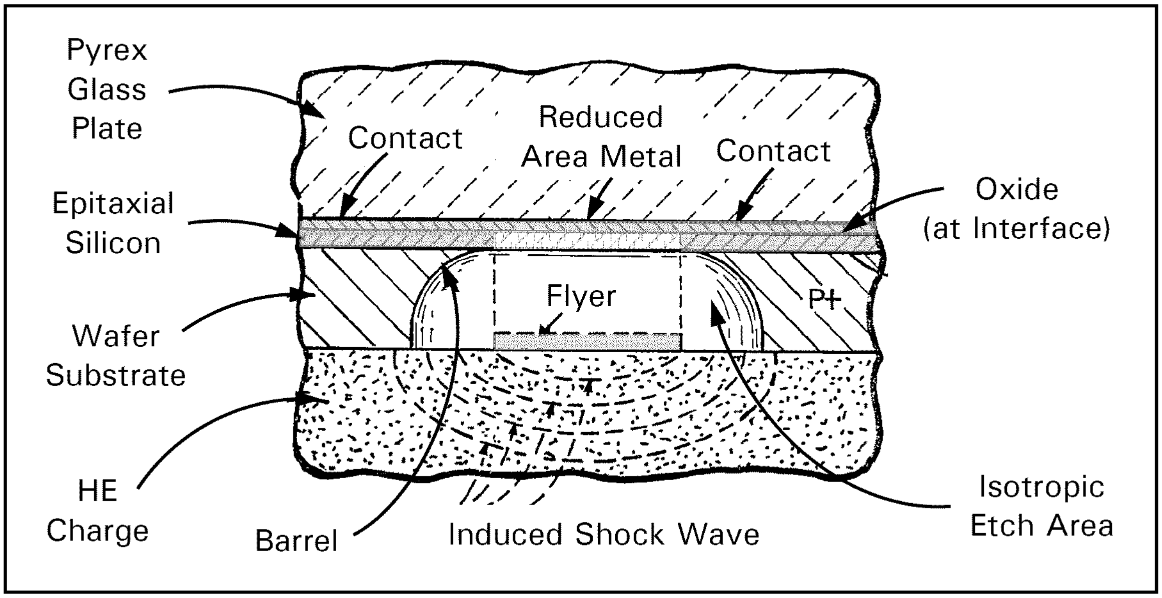

Figure 3-4. Cross-sectional illustration of proposed silicon slapper detonator [14]. Note the flyer and resulting shock wave depict the slapper after firing has occurred.

Obviously, this single device could be repeated multiple times on a silicon wafer to provide many slapper detonators in a single fabrication run. After the steps described in the last paragraph, the wafer would be diced into individual die and post-processing steps would take place. Typical post-processing steps envisioned for this device are the epoxy bonding of a Pyrex glass plate over the center metal area, packaging the device with an appropriate explosive charge, and connecting the contacts to a suitable circuit for firing. The purpose of the Pyrex glass plate is to act as a counter mass for directing the energy from the exploding metal into the direction of the flyer [14].

3.3.2 Microfabricated Slapper Device

In 1993, Henderson, et al. actually fabricated a conceptual slapper device using microelectronic fabrication techniques. In this device, a 635 μm × 635 μm cavity was first formed by etching the surface of the silicon substrate using potassium hydroxide (KOH) [7]. KOH is an anisotropic etchant that etches the silicon much slower in the

(111) crystal plane of the silicon crystal, as opposed to the (100) crystal plane [16]. The overall effect is the formation of a cavity in the silicon substrate as shown in Figure 3-5. This cavity serves as the barrel in their slapper design. The next step involved growing a layer of silicon dioxide over the entire wafer to provide an insulating layer between the substrate and metal, which is the next deposition.

The metal was deposited using two different methods. In one method, the metal was deposited using a lift-off process, which was patterned to provide a reduced metal area in the center of the etched cavity as well as the metal contacts that are located outside the cavity region. This reduced area provides increased resistance that causes vaporization of the metal in this region when a high voltage is applied. Figure 3-6 shows an illustration of the conceptual slapper device fabricated using deposited metal. In the other method, impurity atoms are diffused into the substrate cavity through a silicon dioxide pattern. The diffusion creates a conductive path for current to flow in this region. Electrical contacts, in this second method, are prepared by depositing metal in the region

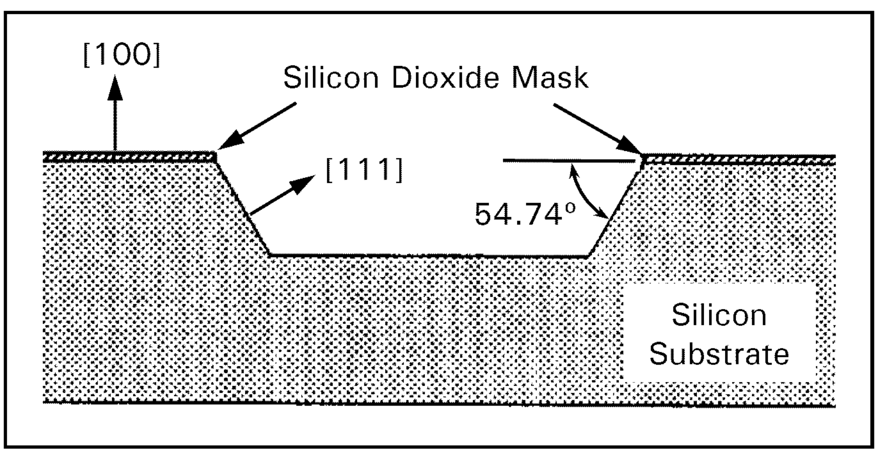

Figure 3-5. An illustration of the preferential etching of silicon by an anisotropic etchant [7]. To protect the areas where etching is not desirable, a layer of silicon dioxide is deposited to prevent the etchant from making contact with the silicon. The bracketed numbers represent specific crystal directions.

outside the cavity by a similar process performed in the first method. Figure 3-7 shows the conceptual slapper device fabricated using diffused impurity atoms. Finally, to complete the fabrication of this slapper device, a drop of polyimide is deposited into the cavity to act as the flyer material [7].

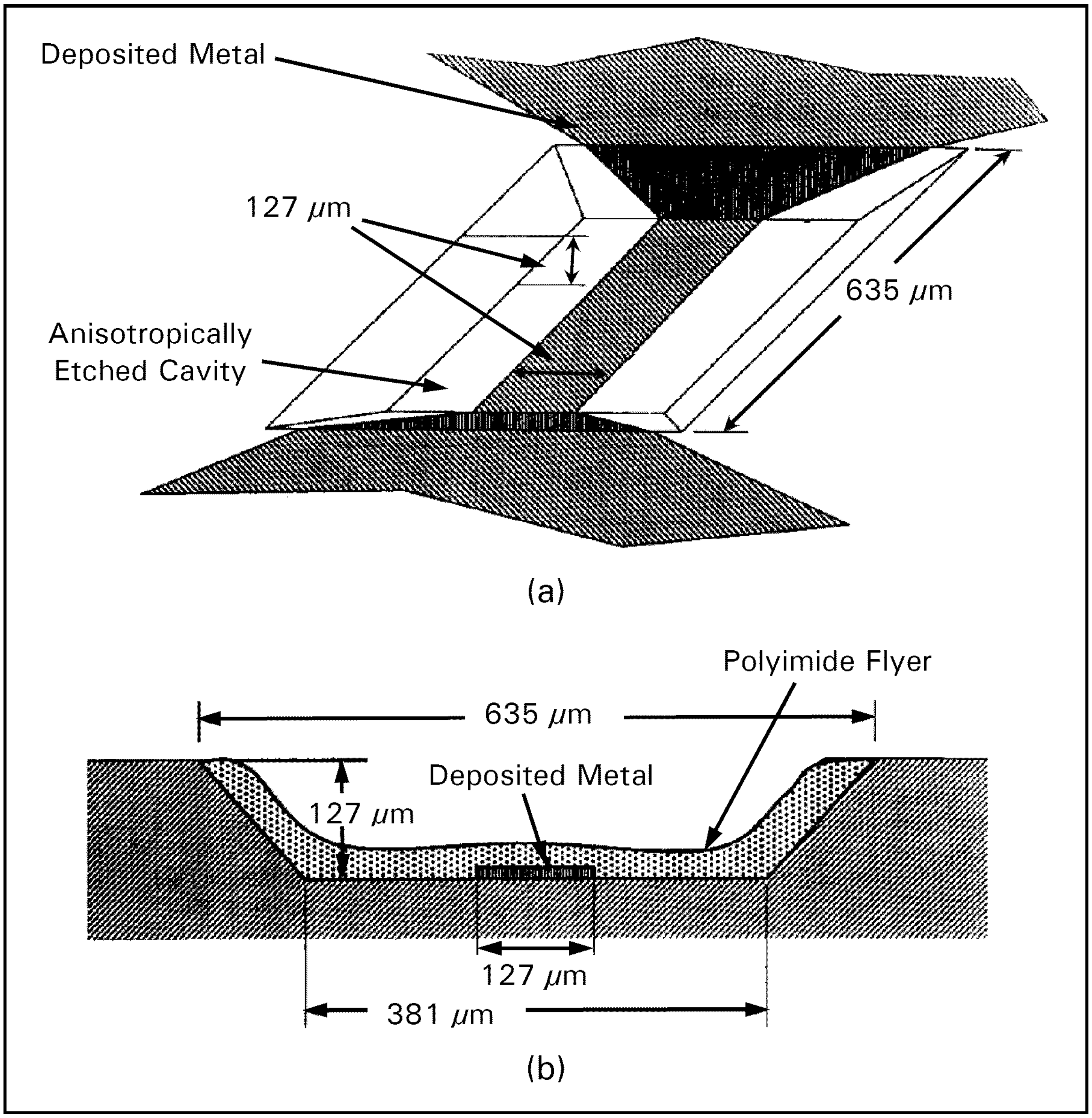

Figure 3-6. (a) Illustration of conceptual slapper device fabricated in a silicon substrate with deposited metal conductor. (b) Cross-sectional view of cavity showing deposited metal conductor [7].

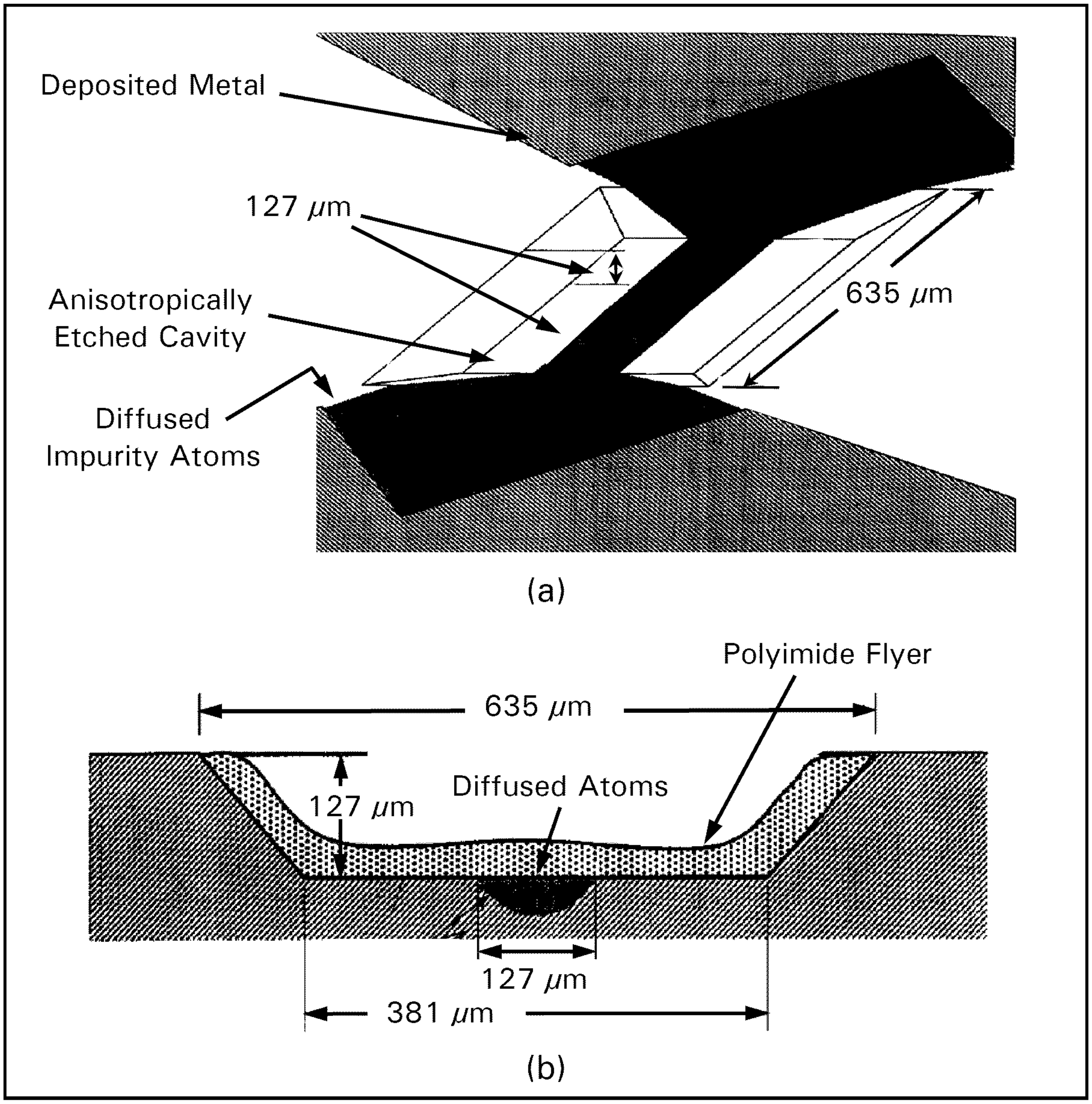

Figure 3-7. (a) Illustration of conceptual slapper device fabricated in a silicon substrate with diffused impurity atoms. (b) Cross-sectional view of cavity showing diffused impurity atoms [7].

Both device types were tested using a high voltage switch that consisted of a bank of capacitors designed to operate at 1 kV and provide 1 J of energy to the bow-tie region. The measured resistance of the metal bow-tie conductor and the diffused bow-tie conductor was 100 mΩ and 95-100 Ω, respectively. When the slapper device was fired, the flyer material was successfully ejected from the cavity in both designs [7]. The kinetic energy produced by the ejected flyer was not measured, and there was no HE pellet incorporated into this slapper design. Therefore, it is difficult to determine whether or not the ejected flyer could have initiated detonation of the follow-on charge. Nevertheless, the fabrication of a conceptual slapper device using microelectronic fabrication techniques was effectively realized.

To show an alternative method for fabricating a slapper device, Henderson et al. also illustrated a conceptual design that consisted of fabricating two separate wafers that can be subsequently bonded together to make up the slapper device. The first wafer functions as the vaporizing metal layer with polyimide deposited on top to act as the flyer. This wafer is fabricated using a diffusion process like the one previously described. Next, three holes are etched completely through the second wafer to provide for a barrel opening and two pass-through areas for the electrical contacts. After processing these two wafers separately, they would be bonded together to make up the slapper detonator [7]. This conceptual device is shown in Figure 3-8.

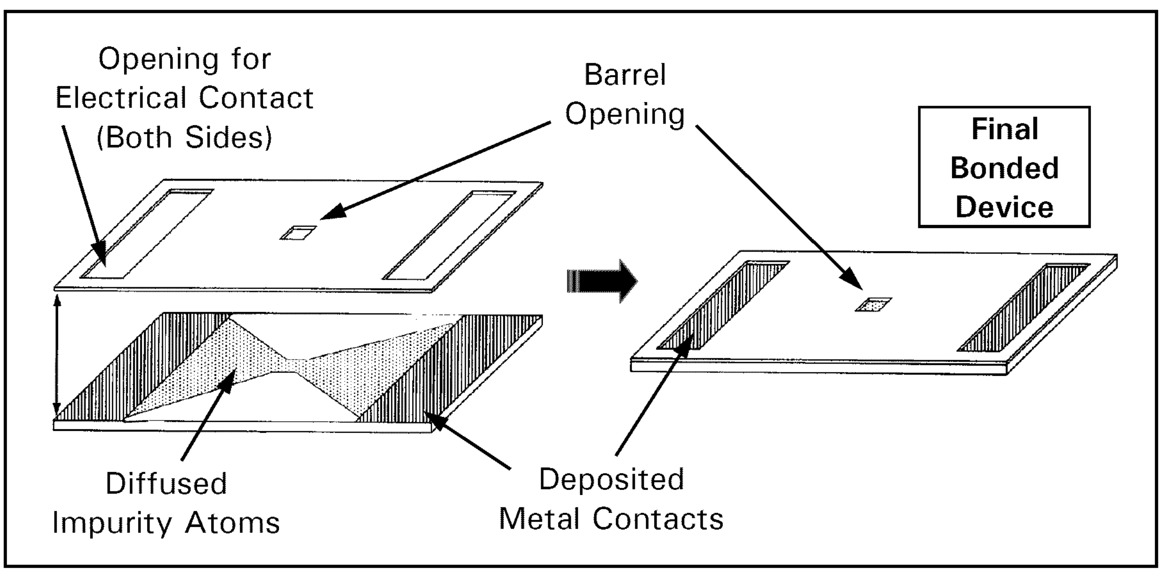

Figure 3-8. Conceptual slapper device produced by bonding two separately fabricated semiconductor wafers [7].

3.3.3 Solid-State Slapper Detonator System

In 1998, O'Brien et al. illustrated the fabrication of a slapper detonator system that includes all the electrical circuitry required to fire the solid-state device. This device includes the capacitor for storing the electrical energy needed to vaporize the metal foil, the switch and trigger circuitry to actually fire the device, the metal foil, and the flyer material. The first series of steps in fabricating this device is the formation of the capacitor. Metal is deposited on the substrate, followed by the deposition of a dielectric layer. Next, another layer of metal and another layer of dielectric are deposited. The two metal layers are placed askew to each other so that electrical connections can be made in later processing steps. The two dielectric layers are placed directly over each other in order to maximize the capacitive area. At this point, the solid-state capacitor is complete; however, additional layer depositions could be used to increase the capacitance value of the device [15]. Figure 3-9 shows both a top and side view of the processing steps completed thus far.

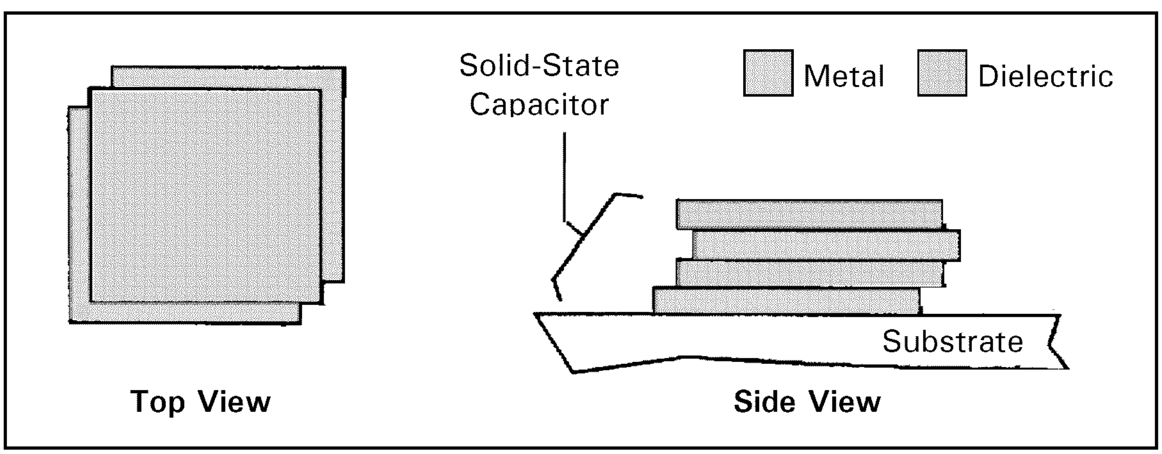

Figure 3-9. Illustration of both the top and side view of the solid-state capacitor fabricated for the slapper detonator system [15].

The second series of steps in fabricating this device is the creation of the switch used to fire the slapper. First, another dielectric layer is deposited on top of the last capacitor dielectric layer. Next, a thin metal layer is deposited askew to the previous layers, so that a small area is exposed. This metal layer will serve as the trigger electrode for the final device. Then, another dielectric layer is deposited followed by a metal layer that becomes the top of the switch. Figure 3-10 illustrates the top and side view of both the solid-state capacitor and switch fabricated for the slapper detonator system. This switch operates by pulsing the trigger electrode to overstress the three dielectric layers in between the two metal layers. When this occurs, a large burst of current is allowed to flow before the switch catastrophically fails [15].

The final series of steps in fabricating this device is the deposition of layers that make up the actual slapper detonator. First, a dielectric layer is deposited to insulate the slapper from the rest of the device. Next, the metal foil layer is deposited to have a reduced area on top and long legs that extend down both sides of the entire device. Connections are made between this top metal layer, the top metal layer of the switch and

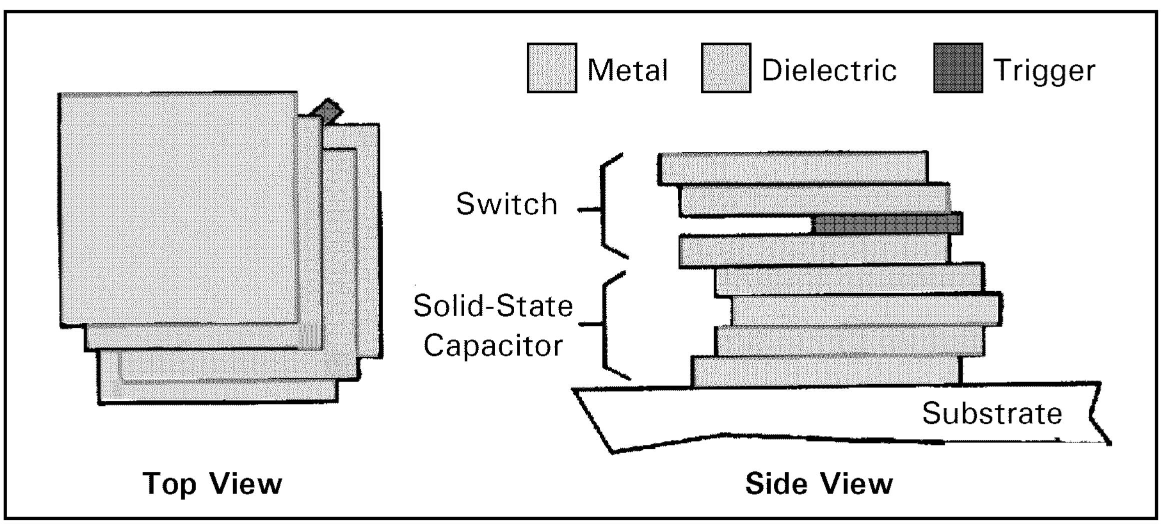

Figure 3-10. Illustration of the top and side view of both the solid-state capacitor and switch fabricated for the slapper detonator system [15].

the bottom metal layer of the capacitor. Finally, the last layer is deposited, which is a polymer that acts as the flyer material. This polymer layer is patterned and etched to expose the reduced area of the metal foil and to function as a barrel (e.g., to shear and direct the flyer material upon activation). Figure 3-11 shows the complete solid-state slapper detonator system including some additional components such as a resistor used to bleed down stray charges in the capacitor, and a circuit used for driving the trigger switch [15]. As with the last slapper device, the kinetic energy produced by this type of detonator is not known. However, the method described here takes the fabrication of a slapper detonator using microelectronic technology one step further by presenting a process in which a complete system could be produced. Clearly, using these fabrication techniques, which have been proven successfully for integrated circuits, would be advantageous for designing next generation fuzes for advanced munition systems.

3.4 Solid-State Slapper Interrupter Concept

Based on the work discussed in the previous section, it is easy to see how modern slapper detonators could be produced in a more efficient and cost effective manner than conventional slapper detonators. Another improvement to the basic slapper design would be to provide some sort of interruption mechanism in-line with the accelerating flyer material in order to provide an additional level of safety for munitions. This interrupter mechanism would have to be capable of preventing the flyer from impacting the HE pellet while in the safe mode, and also have the ability to move out-of-line so that the flyer could impact the HE pellet and initiate detonation. In the safe mode, the interrupter material would have to be able to withstand the energy imparted by the flyer and prevent that energy from passing through to the HE pellet. On the other hand, a requirement for

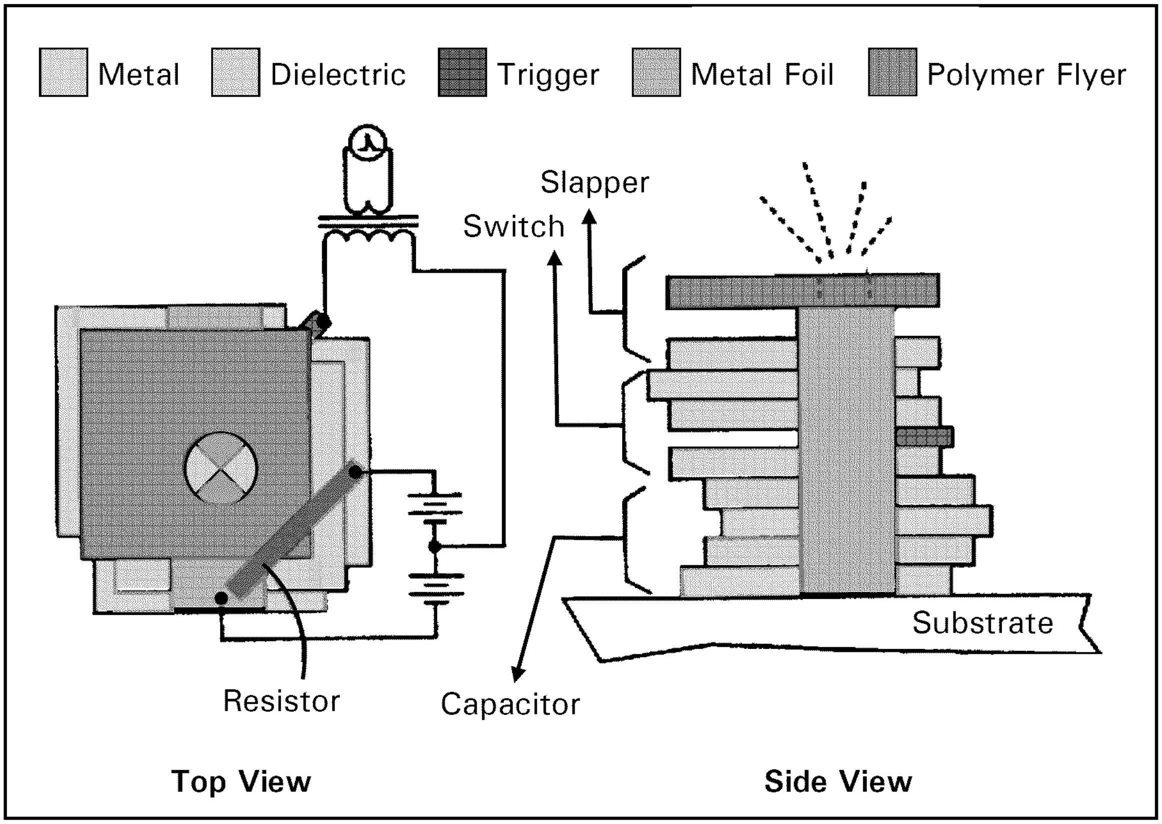

Figure 3-11. Illustration of the top and side view of the complete solid-state slapper detonator system, including a resistor to bleed stray charges in the capacitor, and an external circuit used for driving the trigger switch [15].

the arming mode would be the ability to rapidly move to the out-of-line position quickly enough in response to an activation signal.

Additionally, it would be advantageous for the interrupter mechanism to be capable of sensing at least one of the two independent environmental conditions that prevents unintentional arming and confirms an intentional launch as required by MIL-STD-1316E [17]. Ideally, the energy from this sensed environmental condition could be used either directly or indirectly for actuation of the S&A interrupter device. However, an alternative approach could be to have the environmental sensing function come from an external sensor, which (upon receipt of a valid launch signal) would apply the input necessary to actuate the interrupter. Upon actuation, the interrupter mechanism would move to an out-of-line position and allow a free path for the flyer to impact the HE pellet.

There are several ways that this interruption could be designed. One example does not involve providing an additional interruption component, but entails fixing the HE pellet to an actuator that would move the explosive charge from the safe out-of-line position to the armed in-line position (in relation to the slapper detonator's flyer). This approach was depicted by O'Brien et al. in which it was described that a safely stowed HE pellet could be positioned into an in-line (armed) position through the use of a motor (e.g., an induction motor, a stepper motor, or a piezoelectric motor). Figure 3-12 illustrates this method of explosive train interruption [15].

Another example for an interruption method that does not involve additional components is to move the barrel out-of-line (safe) and in-line (armed), while keeping

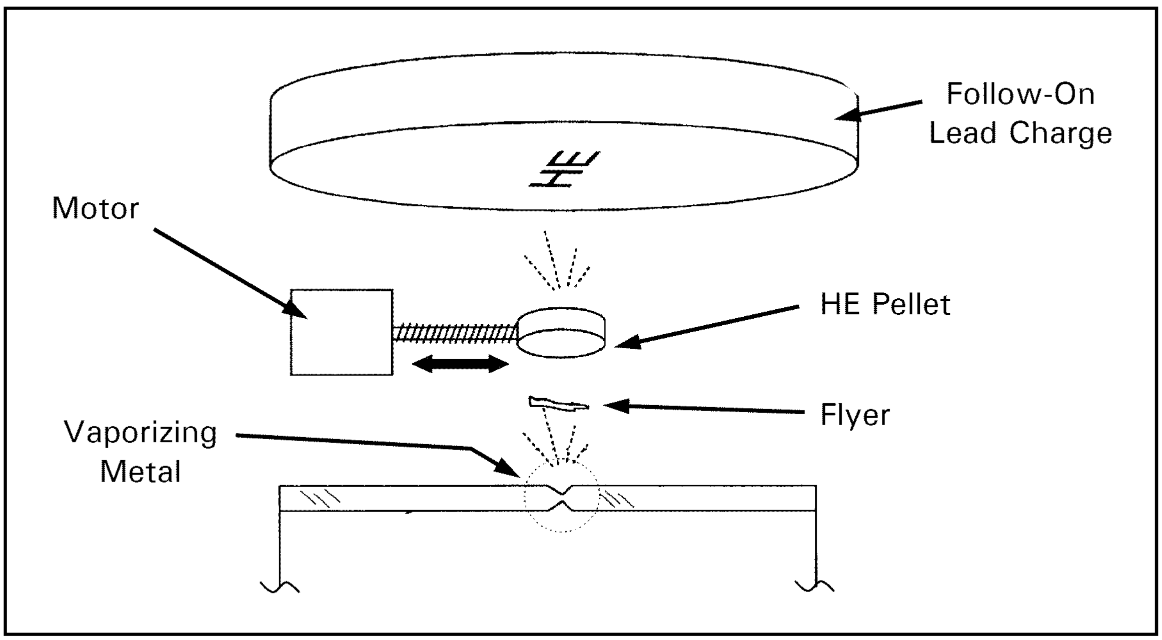

Figure 3-12. Depiction of explosive train interruption by moving the HE pellet out-of-line with the initiating flyer material [15]. The in-line (armed) position in shown.

other elements such as the flyer and HE pellet in a fixed, in-line position. A plate containing the barrel (actually a hole in the barrel plate) could be attached to an actuator capable of moving the barrel in the correct position to shear the flyer and provide a channel to the HE pellet when the slapper is fired. In the case of an inadvertent firing, the barrel plate would be in an out-of-line position with the flyer and explosive detonation would be prevented because impact of the flyer with the HE pellet would be interrupted by the barrel plate. This type of interruption mechanism is described by Garvick et al., in which they suggest the use of MEMS electrothermal actuators as the method to move the barrel plate [2]. A conceptual illustration of their slidable barrel plate is shown in Figure 3-13.

In contrast, an integrated slapper-interrupter mechanism could be designed in which an additional component would be inserted between the flyer and HE pellet.

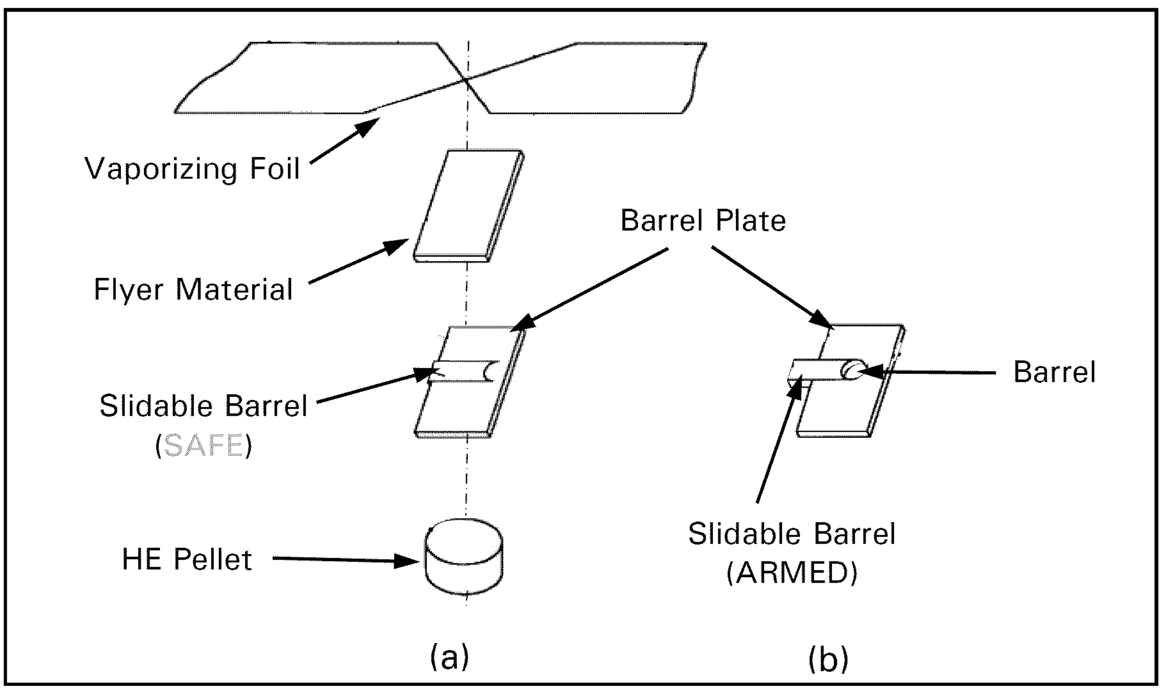

Figure 3-13. Conceptual illustration of an explosive train interruption method using a slidable barrel. (a) Depicts the barrel in the safe position. (b) Depicts the barrel in the armed position [2].

Considering the arrangement of a slapper detonator, the most likely location for an interrupter mechanism to be placed would be after the barrel and before the HE pellet. This location would allow for the flyer and barrel to remain in direct contact with each other, so that the flyer would still be sheared as it accelerated down the barrel. This type of interruption method would also require some sort of actuation device (similar to what was described in the above examples) to move the interrupter from a safe to armed position.

3.5 Introduction of MEMS S&A Interrupter Concept

This leads to the focus of this research, which is to design, fabricate and demonstrate an S&A interrupter mechanism consisting of an opening and closing aperture controlled through the use of MEMS electrothermal actuators. This device consists of four moveable interrupter plates that are normally closed, indicating the safe mode, and opened when in the armed mode. It is envisioned that this interrupter would be used in concert with a solid-state slapper detonator similar to the ones discussed in section 3.3. It is also conceivable that the integration of this interrupter component could be accomplished by bonding the semiconductor wafer containing the fabricated MEMS interrupter to the semiconductor wafer (or layer) functioning as the barrel. This would be similar to the concept shown in Figure 3-8, but with a slight modification. The variation would involve bonding a third semiconductor wafer to the top of the barrel layer shown in Figure 3-8, thus enabling a complete slapper detonator with an integrated S&A interrupter mechanism to be produced. This is illustrated in Figure 3-14 by adding a third layer to the figure presented by Henderson et al. Wafer bonding is a relatively simple process that has proven itself successful in many different areas to include,

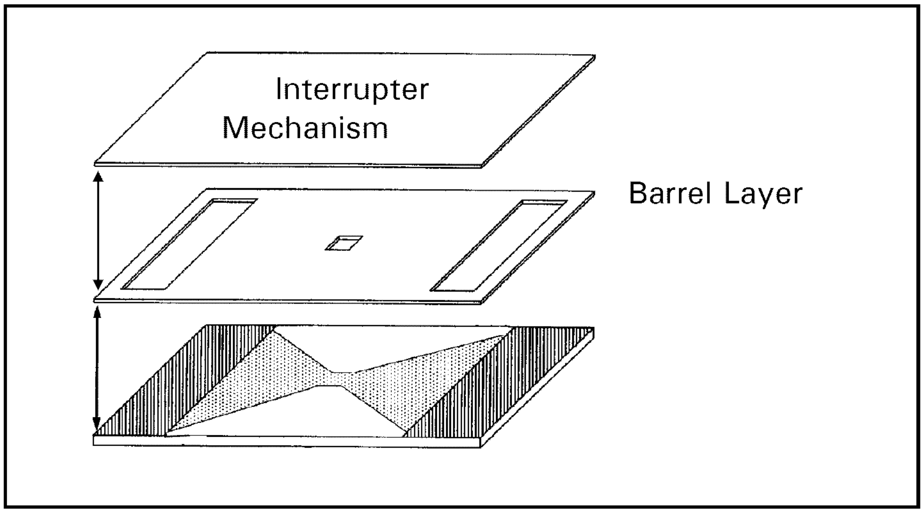

Figure 3-14. Conceptual design for the integration of a MEMS interrupter mechanism with a solid-state slapper detonator. This is a modification of the concept proposed by Henderson et al. [7] and shown in Figure 3-8.

microelectronics, optoelectronics, and MEMS. This process facilitates the fabrication of a variety of devices made up of different material combinations that would be impossible to produce otherwise [18]. The details of designing and fabricating a MEMS interrupter mechanism using a typical surface-micromachining fabrication process will be presented in the next chapter.

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4. Design Theory and Fabrication

While it is true that any microelectronic fabrication technique can be used to fabricate elaborate MEMS devices, typical designers are often constrained (usually by cost and time) to using a proven micromachining foundry process in order to systematically develop the first few iterations in their research effort. These established micromachining fabrication facilities often make available a variety of techniques to accommodate a reasonable amount of design possibilities; however, the fact is that some hard constraints must be incorporated into every fabrication process. These process constraints include such items as: the number of releasable layers; the layer thicknesses; the layer materials; and other inherent process variables that can affect both the electrical and mechanical properties of the final product. In this chapter, the specific fabrication process chosen for this research effort, along with its inherent constraints, will be described. Next, the approach chosen for providing the interruption of the flyer material in a slapper detonator will be presented, along with the theory behind the operation of its main component—the electrothermal actuator. This will be followed by a brief discussion into the operational theory of an electrothermal actuator, as well as the motive for selecting a particular actuator for the interrupter mechanism. Finally, the specific design parameters of the chosen actuator and interrupter mechanism will be presented.

4.1 PolyMUMPs Fabrication Process

The PolyMUMPs is one of three standard processes offered by the commercial program known as MUMPs® (Multi-User MEMS Processes). Specifically, the

PolyMUMPs fabrication process is a three-layer polysilicon surface-micromachining process that is intended to be used for fabricating "proof-of concept MEMS" designs and is not normally used to create production-type devices. The four materials it offers include: polysilicon for the structural layers; a phosphorus-doped oxide (phosphosilicate glass) for the sacrificial layers; silicon nitride for electrical isolation between the polysilicon and silicon substrate; and finally a gold layer used to provide low resistance wires, electrical contact pads, and reflective surfaces. All these layers, except metal, are deposited using a low pressure chemical vapor deposition (LPCVD) process [1]. The metal layer is deposited using electron-beam evaporation at an estimated maximum temperature of 110 °C [2]. The two main advantages of this process are its low cost and reasonable turn-around times of approximately 2 months. This allows for several design iterations to be accomplished in a relatively short amount of time [3]. For example, four design runs were fabricated in this research effort, with the main interrupter design coming out of the third fabrication run.

4.1.1 Sequential Fabrication Procedures

A cross-sectional view of the layers available in the PolyMUMPs process, along with specific material layer names and nominal layer thicknesses are shown in Figure 4-1. The conformal step coverage of this fabrication process, which can be used to manipulate the topology of the upper layers, is clearly depicted in this figure.

The first material to be deposited is silicon nitride, which has a layer thickness of 0.6 μm and serves to insulate the above layers from the heavily doped silicon substrate. This nitride layer is typically not patterned, however it can be reached with a series of oxide etches that are performed using a reactive ion etch (RIE) process. Next, the first

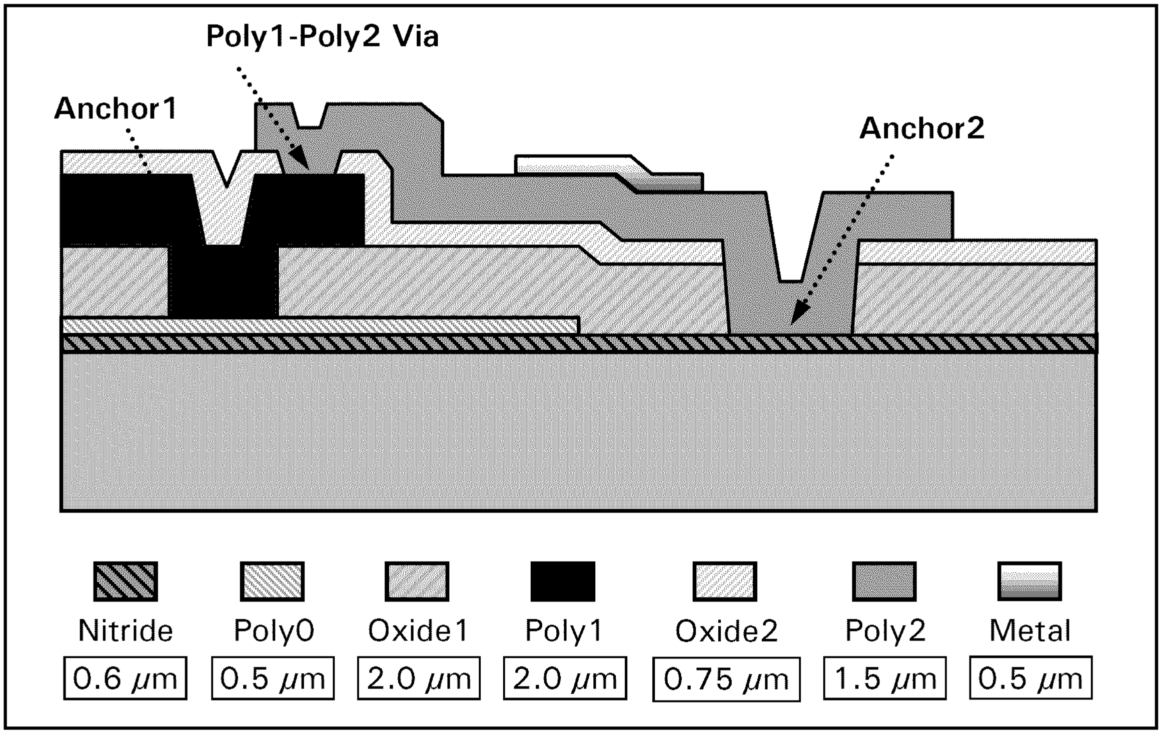

Figure 4-1. Cross-sectional illustration of the PolyMUMPs process (not to scale) [1]. The numbers below the layers represent nominal layer thicknesses and the blue text represents oxide layer etches performed during processing.

structural layer (Poly0) is deposited to a thickness of 0.5 μm. Poly0 is a non-releasable polysilicon layer often used for creating address electrodes and localized wiring. The patterning of the Poly0 layer is realized by using a standard photolithography process followed by a plasma etch. This patterning method is repeated for all of the polysilicon layers. The next step is the deposition of the first sacrificial oxide layer, Oxide1, to a thickness of 2.0 μm. If any contact dimples are necessary in the two releasable structural layers, they are defined by a 0.75-μm deep etch into this oxide layer. Next, the Oxide1 layer is patterned and etched by RIE. The primary purpose of this step is to provide a hole for the first polysilicon layer such that a support anchor can be created [1], [3].

These steps are followed by a 2.0-μm thick layer of polysilicon (Polyl), which is the first releasable layer used to create mechanical structures. A patterning and etch step (similar to Poly0) is then performed to define the dimensions of the Poly1 structure. Next, a second sacrificial layer, Oxide2, is deposited to a thickness of 0.75 μm. This layer then undergoes two patterning and RIE steps. The first one enables a mechanical and electrical connection between the two upper polysilicon layers (Poly1 and Poly2). The second patterning and RIE step removes both Oxide1 and Oxide2 to permit access to either the Poly0 or Nitride layer, such that an anchor support can be formed from the final polysilicon deposition (Poly2). The Poly2 layer has a thickness of 1.5 μm and serves as a second releasable layer for creating mechanical structures. The patterning of this layer is performed using a process similar to the patterning of the other two polysilicon layers. Finally, a 0.5 μm gold layer is deposited, which provides a means for making reflective surfaces, as well as low-resistance wires and electrical contacts [1], [3].

In addition to the material deposition steps, a 1-hour anneal step at 1050°C follows each of the oxide layer depositions. This anneal step serves a dual purpose: 1) to diffuse the phosphorus in the surrounding oxide layers into the structural polysilicon layers to increase its conductivity; and 2) to reduce residual stress. It is important to note that this high temperature anneal makes the PolyMUMPs process incompatible with a simultaneous fabrication of integrated circuit (IC) devices, which generally require carefully timed diffusion steps for proper functioning. Consequently, if it is desirable to fabricate the IC control circuitry for a MEMS device on a single die, then an alternative fabrication process would have to be selected [1], [3].

The final step is to release the upper two polysilicon layers (Poly1 and Poly2) by selectively removing the two sacrificial oxide layers (Oxide1 and Oxide2). In general, release procedures consist of stripping the protective photoresist layer with acetone, etching the sacrificial oxide layers in a hydrofluoric acid (HF) solution, and then finally drying the dies either by direct heating or by using a supercritical carbon dioxide (CO_2) dryer. The specific procedure for releasing the devices used in this research is described in Appendix A. Figure 4-2 shows the hypothetical structure depicted in Figure 4-1 after the release procedure has been performed.

4.1.2 Additional Process Constraints

Some additional constraints to consider in any micromachining process, other than the materials and layer thicknesses are tolerances of the fabrication process that determine specific feature sizes. The PolyMUMPs process offers conservative design rules and precautionary guidelines to assist designers in fabricating MEMS devices that have a high probability of successful operation [1]. However, the minimum feature tolerances can vary between each fabrication run, so a series of test structures are

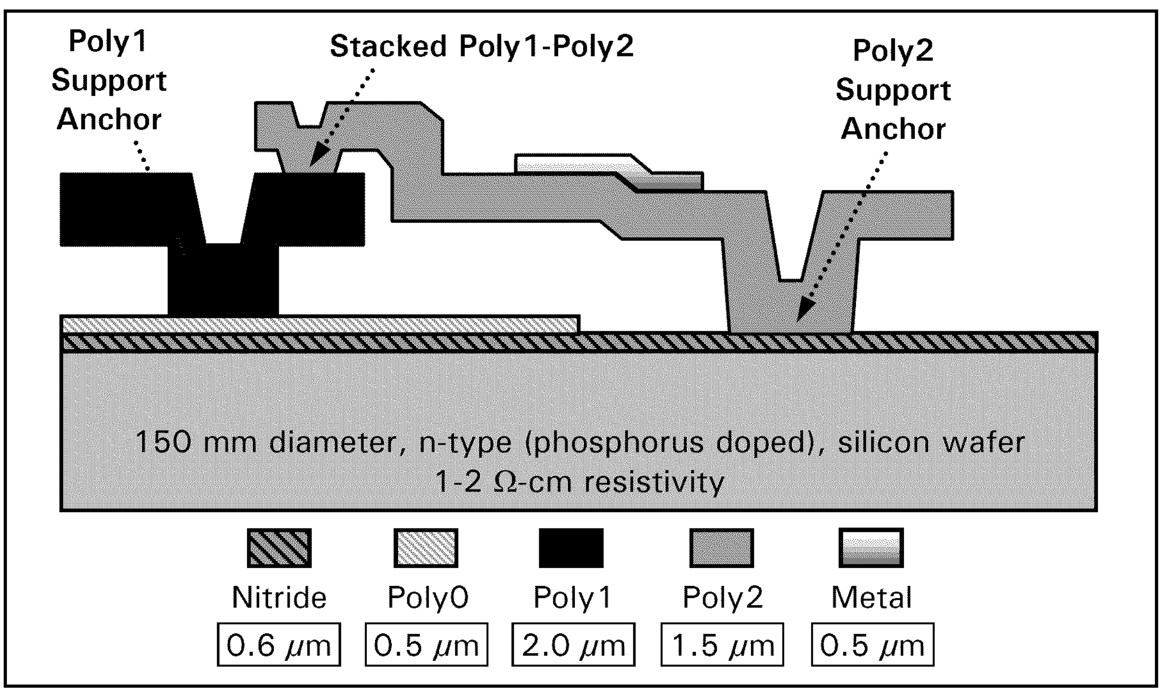

Figure 4-2. Illustration of the released PolyMUMPs structure [1] depicted in Figure 4-1. Note that the sacrificial oxide layers have been etched away by the 48% HF solution.

beneficial in determining the specific process limits for each run. The last two fabrication runs (#68 and #69) for this research effort consisted of test structures designed to observe/measure some of these limits. Specific parameters examined were minimum material widths and minimum spacing between similar materials, i.e., Poly0-to-Poly0, Poly1-to-Poly1, and Poly2-to-Poly2. Figure 4-3 and Figure 4-4 show the test structure design layouts used to determine the minimum fabrication width for all three polysilicon layers and the minimum spacing limits between similar material layers, respectively.

Additionally, the thickness, resistivity, and residual stress for each material layer may vary for each fabrication run. These material properties are measured at the MUMPs® foundry for each fabrication run and are made available to users. This

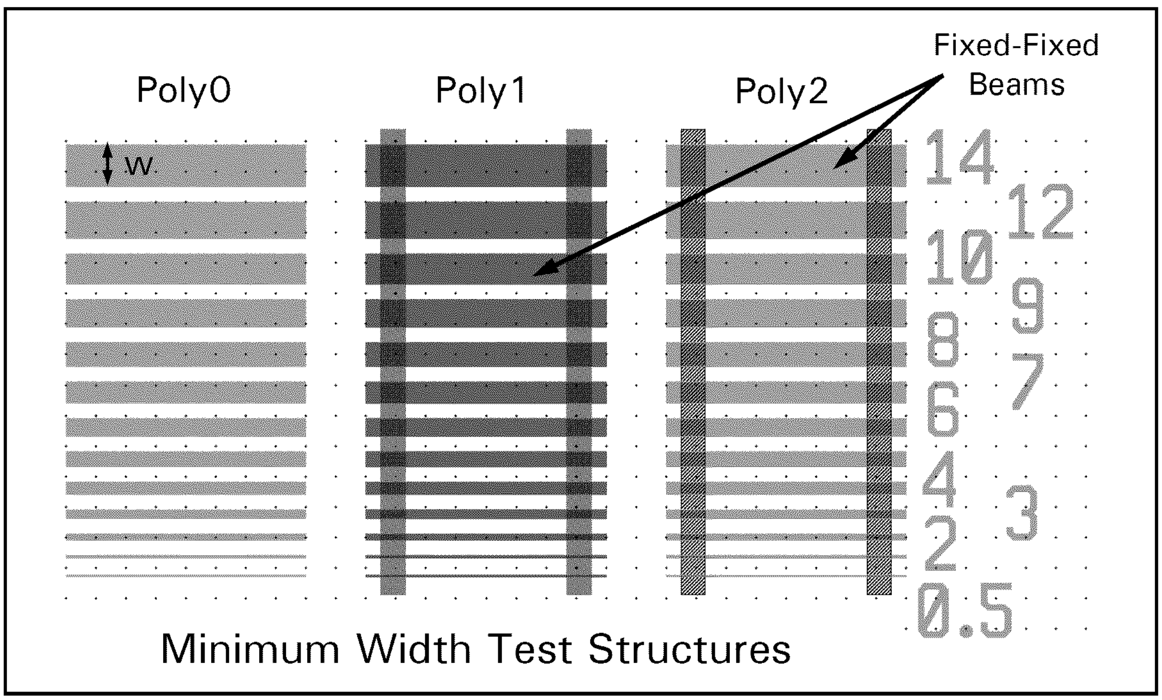

Figure 4-3. Design layout used to determine the minimum fabrication width, w, of all three polysilicon layers. The numbers to the right represent the designed width of each structure, in μm, with the last structure being 0.5 μm and the second to last structure being 1.0 μm. Note: the black dots represent a 10 μm reference grid used in the design layout tool, and the dark vertical bars on the Poly1 and Poly 2 are Anchor1 and Anchor2 etches, respectively.

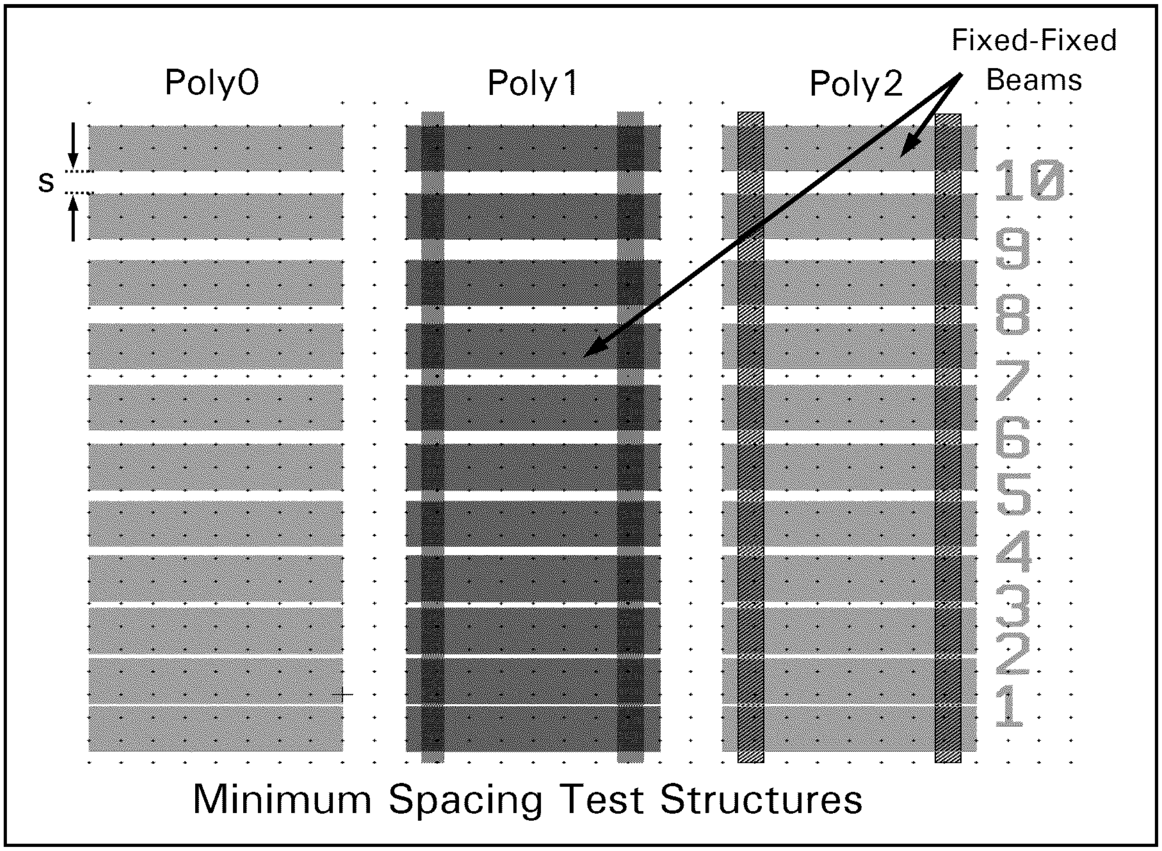

Figure 4-4. Design layout used to determine minimum spacing, *s*, between similar material layers. The numbers to the right represent the spacing between the two adjacent structures, in µm. Again, the black dots represent a 10 µm reference grid, and the dark vertical bars are Anchor1 (Poly1) and Anchor2 (Poly2) etches.

measured data for the four fabrication runs used in this research effort is provided in in Appendix B. However, to get precise thickness data for a specific structure, or to validate the MUMPs® data, a direct measurement of a structure can be acquired by using an optical profiler such as the Zygo Corporation's NewView 5000. This device can obtain vertical measurements, to a resolution greater than 0.1 nm, by using white light interferometry scans [4]. The optical profiler used in this research effort is shown in Figure 4-5.

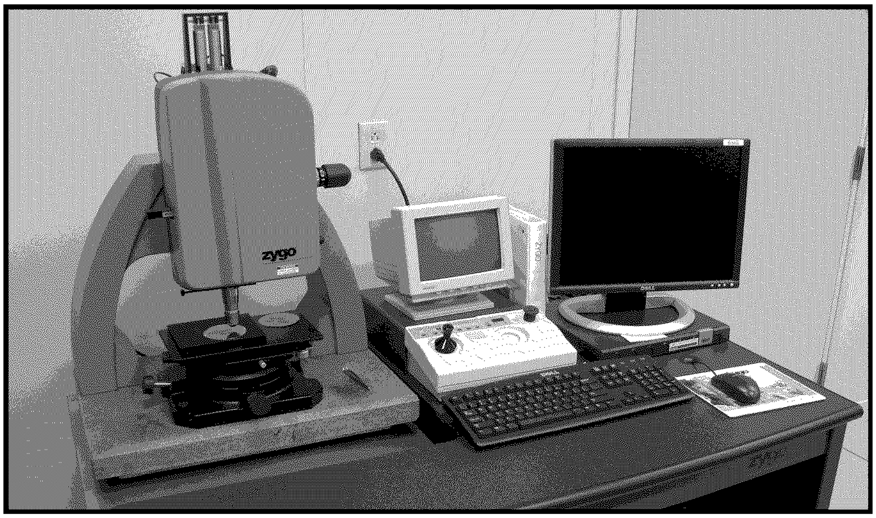

Figure 4-5. Optical profiler used to obtain vertical measurements of fabricated MEMS structures.

4.2 Interruption Method for the MEMS S&A Interrupter

The specific purpose of the S&A interrupter device presented here is to prevent the flyer material in a solid-state slapper detonator from reaching the HE pellet in an explosive train. The interrupter mechanism design consists of four plates, which are each attached to the end of a MEMS electrothermal actuator. The four plates are arranged so that when no power is applied to the actuators, the plates are as close together as possible (ultimately determined by the fabrication process tolerances). In this position, the interrupter prohibits passage of the flyer material, thus preventing the explosive train from detonating. When power is applied to the actuators, the plates move linearly outward, creating an open area for the flyer material to pass through on its way to the HE pellet. Latches are designed for each actuator so that when the proper environmental conditions are satisfied, the mechanism can be permanently latched with the interrupter plates locked in the open (armed) position ensuring that the flyer material can pass through to the HE pellet. If an unlatching capability is desirable, such that the open interrupter plates can be closed (safe), an alternative latching mechanism will be required.