Micromachined Planar Triggered Spark Gap Switch

Thomas A. Baginski, *Senior Member, IEEE*, Robert Neal Dean, *Senior Member, IEEE*, and Edwin J. Wild, *Member, IEEE*

***Abstract*— High voltage switches capable of operating at high speeds with high current levels are used in a variety of applications in commercial and government systems. This paper discusses the fabrication and characterization of a novel micromachined planar triggered spark gap switch. The switch provides a low cost alternative to conventional triggered spark gap switches. The structure is designed for direct integration into the strip-line geometries used in a conventional capacitive discharge unit. The geometry of the device was selected to minimize parasitic impedances associated with conventional firing circuits.**

***Index Terms*— High speed, high voltage switch, low parasitic impedance, low turn-on voltage, microelectromechanical systems.**

I. Introduction

HIGH voltage switches capable of operating at high speeds and over a wide range of voltages and energies are used in a variety of pulse power applications in material science and plasma physics [1]. Of particular interest is the use of small scale capacitor discharges to measure the electrical properties of materials as they are heated from solid through liquid to a gas phase.

In a capacitive discharge unit (CDU), energy stored in a capacitor is coupled through a switch into a low impedance transmission line which typically terminates with a thin sample of material. The energy coupled to the sample is sufficient to cause vaporization. Voltages in such systems range from a few volts to thousands of volts. These vaporized materials are used either as plasma sources for physics experiments, or to propel a thin layer of electrically insulating polymer for high pressure impact studies. Several types of switches have been used to drive these systems including triggered spark gap, dielectric breakdown, and mercury vapor switches [2], [3]. A wide variety of solid-state devices, such as the insulated gate bipolar transistor, are also being utilized for these applications [4]–[7].

The triggered spark gap switch is a three-element, gas-filled, ceramic-to-metal, hermetically sealed pressurized switch that

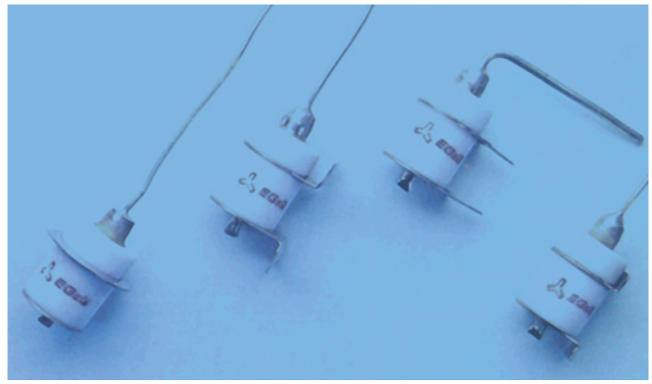

Fig. 1. Examples of triggered spark gaps (courtesy of EG&G).

operates in an arc discharge mode, hence the name "triggered spark gap." The three elements serve as electrodes, where one of the three is a ground or common connection. One of the other electrodes is the trigger and the other is the input. When a voltage of sufficient magnitude is applied between the trigger and the ground, the dielectric material between the two electrodes breaks down resulting in a low impedance arc. Since the arc also extends between the input and the common, low impedance short also exists between these two electrodes, thereby closing the switch. The example spark gap switches shown in Fig. 1 are compact, rugged and designed for high reliability applications. These switches can be switched at speeds of about 70 ns and require a trigger pulse with an energy as low as 500 μJ. Additional key characteristics of these triggered spark gap switches are their small size, high speed and ability to withstand extreme shock, temperature and vibration. These switches will reliably fire over 100 shots at moderate peak currents (approximately 1500 A peak) [8]. Triggered spark gap switches have been in use for many years, providing precision in timing and activation of in-flight functions such as rocket motor ignition and missile stage separation. Each of these applications involves the activation of electro-explosive devices such as an exploding bridge-wire or an exploding foil initiator (EFI) [9]–[12]. Another application for spark gap switches is electro-static discharge suppression [13].

The high voltage switch presented in this paper has been designed for multiple use, testable alternative to the more expensive triggered spark gap switches and equivalent solid-state devices. The micromachined planar triggered spark gap switch is intended for large volume, relatively inexpensive

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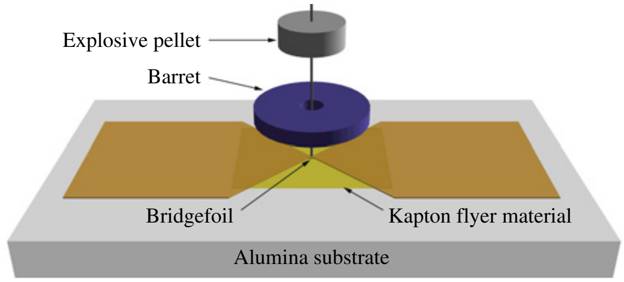


Fig. 2. 3-D illustration of slapper components.

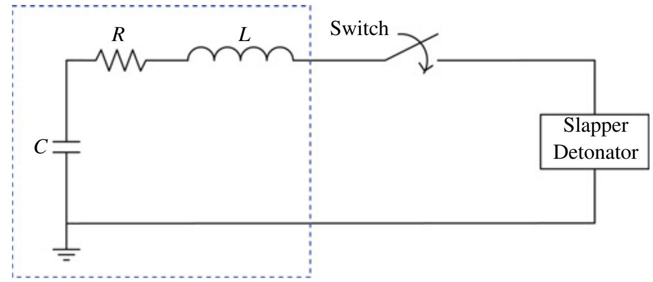


Fig. 3. Schematic representation of a CDU connected to a slapper and switch.

systems and as a cost effective switch for use in destructive testing. The switch presented here has been designed specifically for initiation systems incorporating EFI detonators. EFIs (also referred to as slappers) have very stringent firing characteristics and were used as a test vehicle to verify correct micromachined planar triggered spark gap switch operation [14].

Correct actuation of an EFI requires a switch with certain minimal electrical characteristics. These desired characteristics include (but are not limited to):

1) standoff voltage greater than 1500 V;
2) switch should allow fast discharge of a high voltage capacitor with a discharge time (τ) less than 100 ns;
3) fabrication should employ a simple layout that allows direct integration into strip-line geometries (i.e., minimize parasitic impedances);
4) monolithic construction should be employed using conventional microfabrication techniques to make the switch mechanically robust;
5) reliable multi-shot capability.

To better understand the electrical and mechanical requirements placed upon the switch, a brief overview of the EFI detonator is presented here. The basic features of an EFI are presented pictorially in Fig. 2. The starting substrate (usually a ceramic, such as alumina [15]) is coated with a thin film of metal and then etched to realize a bowtie configuration. The narrow portion of the bowtie is called the bridgefoil. The bowtie is then covered with a suitable dielectric material to form the flyer. The flyer is that portion of the dielectric film that is initially in intimate contact with the bridgefoil. A polyimide material such as Kapton is a typical flyer material which can be spun on using ordinary photoresist processing techniques. A dielectric material is used for a barrel which is placed in intimate contact with the substrate. An explosive pellet is then placed in direct contact with the barrel. The slapper is typically placed in a circuit with a CDU and switch, as illustrated in Fig. 3.

An EFI functions by converting the stored electrical energy of the CDU into the kinetic energy of a thin flyer plate. When the spark gap switch between the CDU and the slapper closes, the resulting electrical current density in the bridgefoil reaches about 200 million A/cm^2. This extremely rapid introduction of electrical energy into the bridgefoil, reaching several times the vaporization energy of the foil material, converts the foil into a high temperature, high pressure gas. This gas pushes on the thin flyer (and on the substrate), causing the flyer to shear, and then accelerating it to the velocities in the range of 3–5 km/s [16], [17].

The barrel, which separates the flyer from the explosive pellet, provides the flight distance necessary for the flyer to reach these velocities upon vaporization of the foil. The flyer is accelerated down the barrel and impacts the explosive pellet. The impact creates a mechanical stimulus that is sufficient to cause almost instantaneous detonation of the explosive pellet. The actual initiation of the explosive pellet occurs in about 10 ns, making the shock wave appear to have a magnitude of approximately 100 000 atmospheres [18], [19].

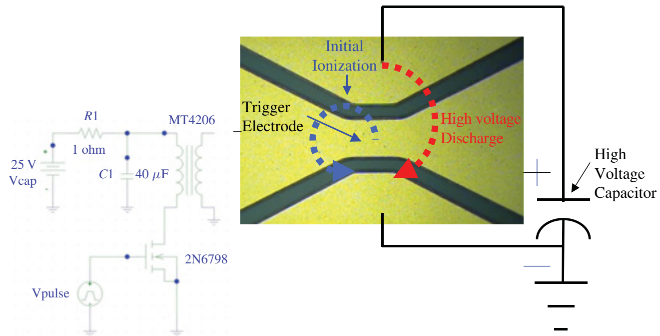
II. Micromachined Planar Triggered Spark Gap Switch Fabrication

A top view photograph of a micromachined planar triggered spark gap switch is presented in Fig. 4(a). A high voltage capacitor, connected between the anode and cathode of the switch, is illustrated. The schematic capture tool of PSPICE was used to illustrate the equivalent circuit which discharged a 40 μF capacitor into the primary of the trigger transformer (MT4206). Vpulse represents a standard pulse generator. M1 is a MOS transistor (2N6798).

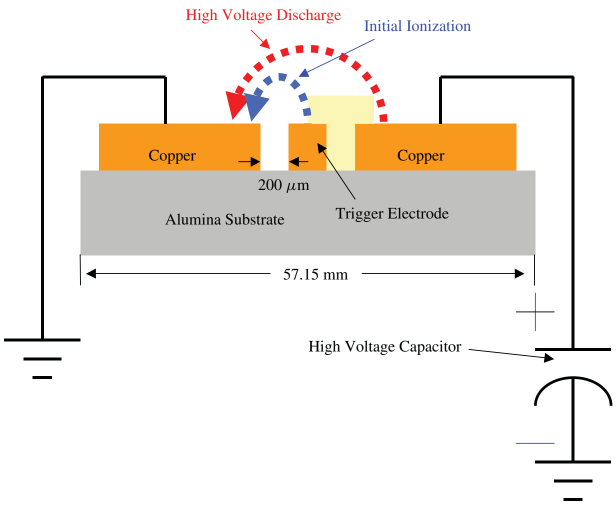
A side view representation is portrayed in Fig. 4(b). The yellow block between the high voltage electrode and the trigger electrode represents the region where initial high voltage discharge (i.e., breakdown) occurs. It was fabricated utilizing standard microelectromechanical systems fabrication techniques [20]. The starting material for constructing the switch is a 57.15 mm $\times$ 57.15 mm $\times$ 0.635 mm thick ($\pm$25 μm) 99.6% pure alumina substrate, with a polished 25.4 nm maximum surface finish on one side only. The back-side of the substrate is lapped to a 0.254 μm nominal finish, typical of what is used in the hybrid electronics industry [21]–[23]. The fabrication process began by baking the substrates at 500 °C in a Thermco oxidation and diffusion furnace with a dry nitrogen ambient to dehydrate the surface.

The substrates were then placed in a Varian Mark 60 E-beam evaporator possessing an Ar-ion gun cleaning system. An Ar-ion ablation surface clean was performed at a background pressure of 0.1–0.3 mtorr. For this step, the ion beam current was 30 mA, the discharge voltage was 40 V and the bias voltage was 1000 V during the surface clean.

A three-level vapor deposition was then performed with 500 Å of Ti as an adhesion promoter, 20 μm of Cu as a conductor and 500 Å of Au as an oxidation inhibitor. It should



(a)



(b)

Fig. 4. (a) Top view photograph of the micromachined planar triggered spark gap switch. (b) Side view representation of the micromachined planar triggered spark gap switch.

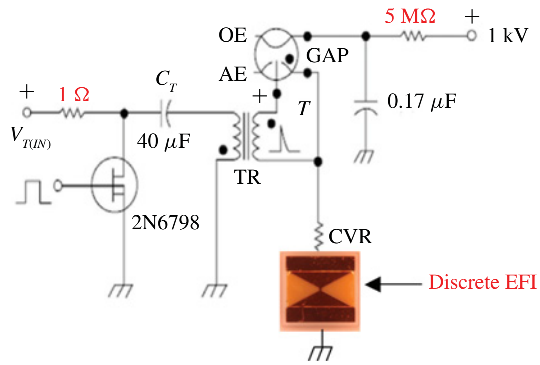


Fig. 5. Conventional fireset.

be noted that a copper/gold electroplating process on a thin Cu seed layer could be utilized instead of electron beam evaporation. Upon removal from the deposition chamber, the substrates were immediately spin coated at 2900 rpm with positive photoresist, Shipley 1045, and softbaked at 90 °C for 35 min in a convection oven with a nitrogen ambient. The typical photoresist thickness after the spin and softbake cycle was 4 μm.

The coated substrates were exposed for 30 s using contact lithography (Suss MABA6) and developed with 1:4 [AZ351 developer: de-ionized water (DI)] for 1.5 min. The substrates were then rinsed in DI for 30 s and dried with blown nitrogen gas. The substrates were reinserted into the Varian Mark 60 deposition chamber and Ar sputter etched for 5 min with the same parameters listed previously, in order to remove the exposed Au. After removal from the chamber, the exposed Cu was etched with a solution consisting of 25 mL H_2SO_4 : 25 mL H_2O_2 : 900 mL H_2O (DI water). Next, the exposed Ti was etched with a solution of 1 mL HF : 100 mL CH_3COOH : 100 mL H_2O (DI water). The substrates were then rinsed in DI water for 5 min and dried with a nitrogen jet. The photoresist was removed by immersing the substrates first in acetone, then methanol, followed by a DI water rinse and dried with blown nitrogen.

After inspection, a first coat of polyimide (PI 5878G) was spun on at 1500 rpm and baked for 30 min at 90 °C in a nitrogen filled convection oven. A second polyimide coat was then spun on at 1500 rpm and baked for 45 min at 125 °C. The two-coat process minimizes bubbles formed by out gassing solvents diffusing through the polyimide. The final cure of the polyimide was achieved by baking the substrates at 350 °C for 1 h in a nitrogen ambient. The substrates were oriented in a horizontal position during all curing cycles.

Next, the substrates were conventionally diced using a Dicing Technology type CX blade (010-325-040J). After inspection, a mechanical blade was utilized to pattern the polyimide and expose the surface of the metal. It is noted that the polyimide could be patterned with a conventional alkali developer or an reactive ion etching process if another mask level was added to the process. The size of the completed die was 10.16 mm × 10.16 mm [24].

III. Micromachined Planar Triggered Spark Gap Switch Testing

The goal of this effort was to demonstrate that the micromachined planar triggered spark gap switch could effectively replace a conventional triggered spark gap switch. A standard fireset was constructed and is illustrated in Fig. 5. A pulse generator was utilized to discharge C_T (40 μF electrolytic capacitor charged to 25VDC) into the primary winding of the trigger transformer. The output of the transformer (MT4206) was connected between the central trigger electrode of the switch and circuit ground. A current viewing resistor (CVR = 0.00249 Ω) was connected in series to allow the discharge waveform to be monitored. The high voltage capacitor was measured as 0.17 μF and was typically charged to 1 kV. The EFI was inserted in a series with the high voltage capacitor. All connections of the high voltage discharge path were made using copper stripline to minimize parasitic resistance and inductance [25], [26].

The following sequence describes the operation of the high voltage switch. Actuation of the switch is achieved by applying a high potential voltage between the trigger electrode and ground potential. This trigger signal results in ionization of the area between the trigger and the ground potential. The ionized plasma propagates and expands, till it approaches the high voltage electrode. When the ionized gas makes contact with the high voltage electrode, the 0.17 μF capacitor is then able to discharge across the low impedance ionized gas

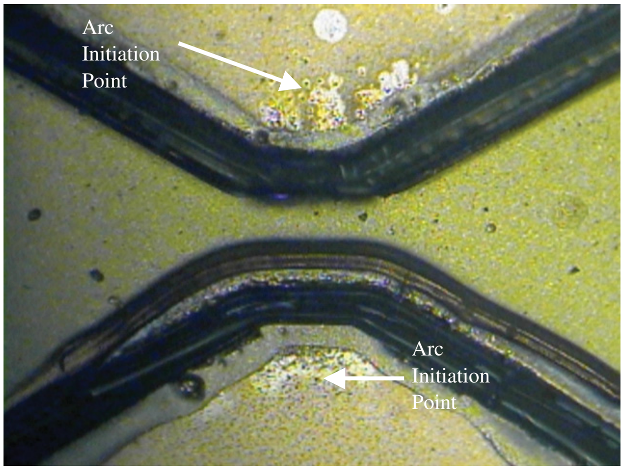


Fig. 6. Photograph of metal electrodes of a micromachined planar triggered spark gap switch.

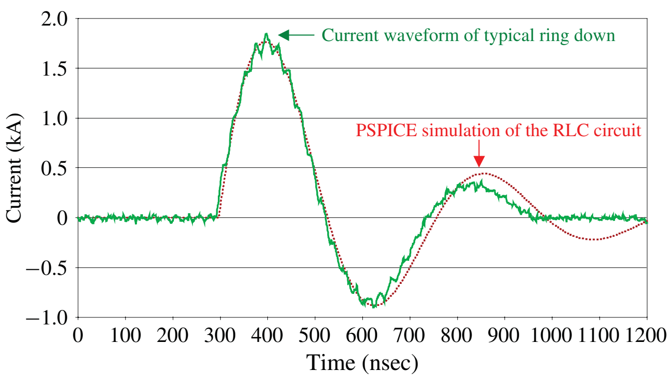


Fig. 7. Measured current waveform of a typical ring down and PSPICE simulation of the resistance-inductance-capacitance (RLC) circuit.

in the gap. The device can be integrally packaged with a stripline geometry in order to reduce interconnect parasitic impedances to a minimum. A photograph of metal electrodes of a micromachined planar triggered spark gap switch after 20 discharges of 1 kV with a 0.17 μF capacitor is presented in Fig. 6. It is noted that land areas from where the arc initiates and terminates show essentially no damage. Sample micromachined planar triggered spark gap switches were typically fired several dozen times before any degradation of metal composing the lands was observed.

In order to verify correct operation of the switch, two sets of experiments were performed. The first experiment was a determination of the value of the fire set inductance, L, and resistance, R, as previously illustrated in Fig. 3. For this experiment, a piece of copper foil replaced the slapper detonator. The capacitor (0.17 μF) was charged to 1000 V and allowed to discharge into the strip line in order to generate the conventional current waveform of a RLC ring down. The CVR was placed in series to the sample current flow in the circuit as a function of time. A representative sampled current waveform as a function of time is illustrated in Fig. 7. All switches were subjected to a high voltage stress test prior to being soldered into a firing circuit with an explosive detonator. The goal of

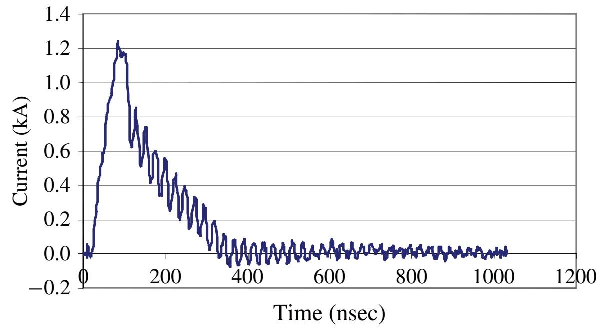


Fig. 8. Typical current trace during firing of a LEEFI.

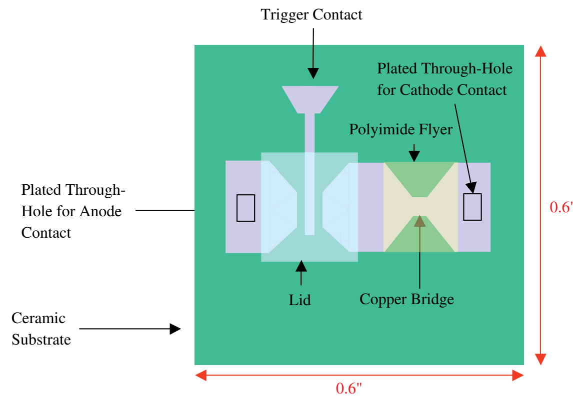


Fig. 9. Top view of an EFI switch module.

the stress test was to eliminate any device which could not sustain a voltage of 1500 V (one of the five desired switch characteristics stated previously) between anode and cathode. Switches which passed the stress test were then utilized for subsequent electrical characterization.

The equivalent series inductance (L) of the fireset was calculated as 30 nH and the series equivalent resistance (R) was calculated to be 180 mΩ. It is noted that the resistance of the foil contact was a significant component of the resistance. The jitter observed between the trigger pulse and discharge of the 0.17-μF capacitor was commensurate with a commercially available triggered spark gap switch. A PSPICE simulation of the RLC circuit is also illustrated in Fig. 7.

The second experiment consisted of testing the ability of the micromachined planar triggered spark gap switch to actuate a commercially available slapper. The resistive foil used for the ring down of the fireset was replaced with a commercially available low energy EFI (LEEFI). A series of test firings were performed at various charging voltages to determine the firing threshold of the EFI when functioned in this circuit. A typical current trace is presented in Fig. 8. It is noted that a ground loop (as evidenced by circuit ringing) was present in the firing circuit. All explosive tests were performed at the Fuzing Branch located at Eglin AFB (Florida, USA). The practical time limits imposed by scheduling constraints did not allow for the location and mitigation of the ground loop. Therefore the limited time available for explosive testing was utilized to determine the operating characteristics of the switch. In subsequent tests, the switch successfully functioned

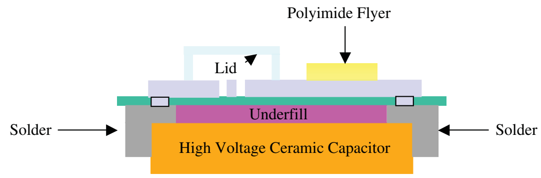


Fig. 10. Side view of an EFI switch module.

slapper detonators at various firing voltages. The explosive utilized was HNS-IV [27]. No current or voltage data were acquired on the primary of the trigger transformer during switch characterization due to the limited number of electrical feed throughs of the explosive test chamber. The overall performance was noted to commensurate with a commercially available triggered spark gap switch.

Commercial EFIs are typically fabricated with conventional thin film processing techniques on ceramic substrates. The triggered spark gap switch was designed to be incorporated onto the same substrate and fabricated during the same process steps as the EFI. This integration of components will reduce packaging costs significantly.

A proposed packaging concept of an integrated EFI module is portrayed in Fig. 9 (top view) and Fig. 10 (side view). The module consists of three primary components: a LEEFI (i.e., copper bridge with a polyimide flyer), a high voltage ceramic capacitor and the triggered spark gap switch. The EFI and switch would be fabricated simultaneously on a ceramic substrate. The substrate would be directly attached to the firing capacitor (via feed-throughs). This fabrication scheme results in the most efficient coupling of electrical energy from the capacitor to the bridge of the EFI by absolutely minimizing the equivalent series resistance and inductance of the firing circuit. The substrate could also provide an area for any secondary surface mount components necessary to trigger the switch. The arrangement of all the three components on one common substrate would result in reduced packaging costs as compared to a conventional fireset assembled with discrete components.

IV. Conclusion

A novel replacement for a conventional triggered spark gap switch has been introduced. The structure is simple to construct using standard microfabrication processing techniques. Test devices were successfully fabricated and evaluated. The resulting micromachined planar triggered spark gap switch is easily integrated into flat stripline geometries. An evaluation fireset circuit containing a micromachined planar triggered spark gap switch demonstrated the ability to successfully detonate a commercially available LEEFI.

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