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Novel Electroexplosive Device Incorporating a Reactive Laminated Metallic Bridge

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The description and characterization of a novel, low firing-current, semiconductor-based, scaleable monolithic electroexplosive device is presented. The device consists of a metallic (palladium) bowtie-shaped heating element, which has been selectively coated with a reactive metal (zirconium) to enhance ignition of a conventional pyrotechnic mix. Integrated diodes provide protection against electro-static discharge events. The device was specifically configured to allow ease of interconnect by wirebonds, conductive epoxy, or solder. The structure was fabricated with conventional microelectronic techniques that allow for very economical manufacturing. Extensive design validation testing was performed. Parts with <1.2A/1 ms all-fire, >0.5A/10 s no-fire at 99.999% reliability/95% confidence and function time to peak pressure of <1 ms were demonstrated.

Nomenclature

$D1$, $D2$	=	shunting diodes
I	=	firing current
Q	=	firing energy
R	=	resistance of bridgewire
T	=	time period over which firing current is integrated

I. Introduction

WITHIN a broad variety of commercial and government ordnance systems, there exists an interface that uses electrical energy to initiate an exothermic reaction (i.e., combustion, deflagration, detonation).[1,2] The structure, which performs this function, is commonly referred to as an electroexplosive device (EED). A typical EED is illustrated in Fig. 1 (Ref. 1).

The basic components of an EED are a header assembly, which contains lead pins connected to a thin metallic wire, and a charge holder, which contains energetic compounds. The thin metallic wire is primarily resistive and commonly referred to as a bridgewire. Actuation of the device is achieved by passing a current through the bridgewire until the temperature of the wire reaches the ignition point of the priming compound.[1]

The utilization of microelectronic fabrication techniques provides various advantages in the manufacturing of electroexplosive devices. These advantages include the ability to construct large volumes of identical devices with very repeatable characteristics at low cost, utilization of feature sizes significantly smaller than what can be achieved with conventional bridgewire processes, and the use of novel bridge materials to enhance ignition and integration of other electrical components directly on a chip.[1–5]

The purpose of this paper is to introduce a solid-state EED that embodies all of the advantages just mentioned, plus demonstrates the ability to generate large amounts of highly reactive plasma at low-voltage and low-current conditions. The device is compatible with existing constant current firesets used to drive bridgewires while providing a reliable (i.e., high plasma output) ignition source.

Aerospace applications include small, fast rocket motor initiators and piston actuators (Data available on-line at http://www.quanticindustries.com/Quantic/ord.htm). Further advantages of the device, relative to bridgewire parts, are fast function times (<0.1 ms) and low firing energies (<300 μJ) while being able to withstand extreme electrostatic discharge (ESD) conditions, i.e. 25,000-V potential on a 150-pF capacitor discharged into the bridge via 150 Ω. The structure is referred to as a constant current semiconductor bridge (CCSCB).

II. Fabrication

Starting material for the devices was ⟨111⟩ orientated, 300 mΩ-cm, 610-μm thick n-type silicon wafers polished on one side. The wafers were cleaned and thermally oxidized to form a layer of silicon dioxide (SiO_2) on the surface that was ≅1 μm thick. The wafers were then coated with photoresist, and the SiO_2 was selectively etched to form contact windows.

A layer of aluminum (≅1 μm) was then sputtered onto the surface of the wafers and selectively etched to conform to the shape of the previously etched contact windows. The remaining aluminum was then alloyed with the silicon at 450°C for 30 min. The resulting silicon/aluminum interfaces formed Schottky barrier diodes $D1$ and $D2$ shown in Fig. 2 (Ref. 6).

A layer of titanium (≅500 Å)/palladium (≅2100 Å) was deposited over the aluminum and then selectively patterned to simultaneously form a butted contact with the Schottky diodes and a bowtie-shaped ignition element (i.e., bridge).[7] The titanium was deposited first to act as an adhesion promoter. Palladium was used for its resistance to corrosion and relatively high resistivity (9.93 $\mu\Omega$-cm). The thickness of the palladium was specifically chosen to result in a final bridge resistance of 2 Ω (see Fig. 3). The thickness of the bridge could easily be varied to provide any practical value of resistance required.

A layer of titanium (≅500 Å)/nickel (≅1500 Å)/gold (≅1000 Å) was then selectively deposited over the aluminum/palladium contact pads to provide a surface layer, which could be contacted via wirebonds, conductive epoxy, or solder. The titanium was deposited first

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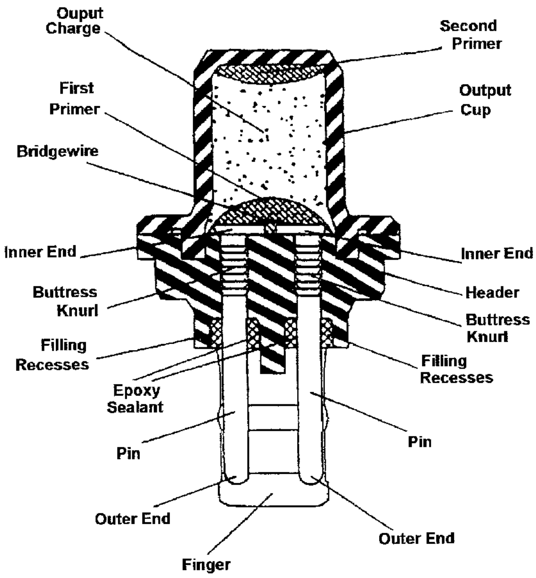

Fig. 1 Typical EED.

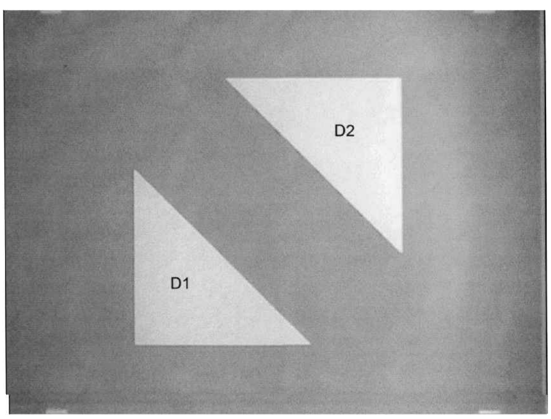

Fig. 2 Schottky barrier diodes.

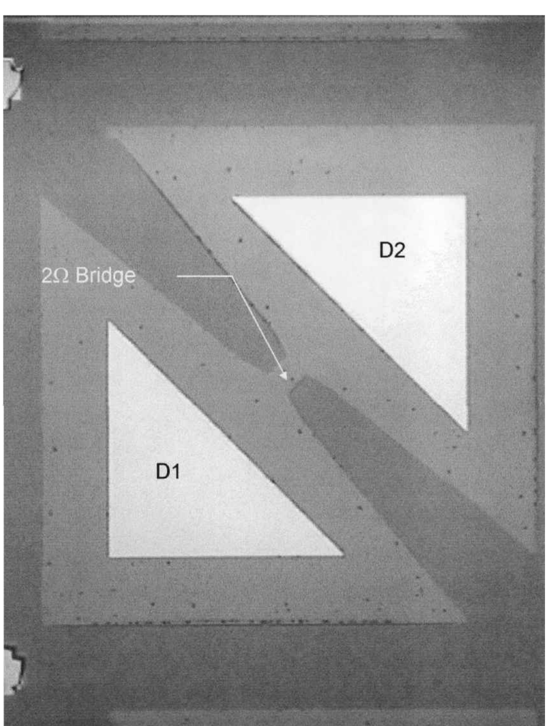

Fig. 3 Palladium bridge.

and provides adhesion to the palladium. The nickel was deposited next to provide a solderable surface material. The gold was then deposited to provide an oxidation barrier for the nickel and can also be used for wirebond attachment. During soldering, the gold dissolves into the solder and thereby assists in providing a clean, oxide-free nickel surface for solder contact (see Fig. 4).

The final step in fabrication was the selective application of a layer of zirconium (≅9000 Å) over the bowtie-heating element. The zirconium serves two primary functions: structural reinforcement of the palladium bridge and a source material for a chemically reactive plasma. A completed device is shown in Fig. 5. A schematic side view representation of a device is shown in Fig. 6.

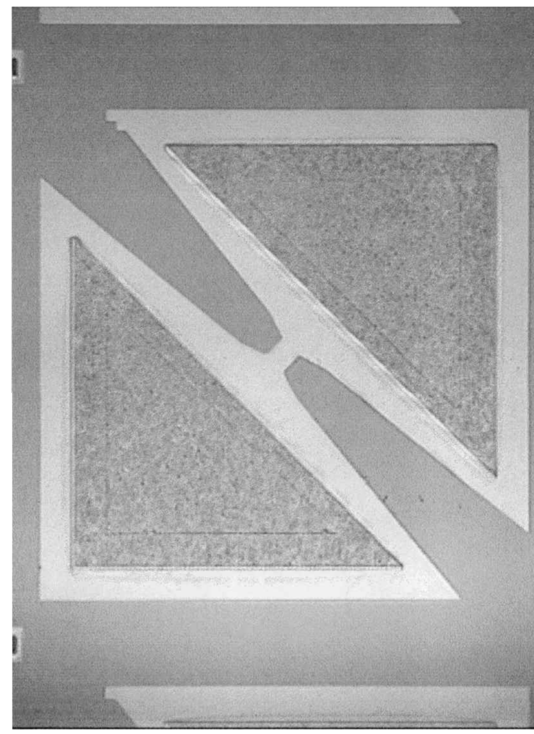

Fig. 4 Titanium/nickel/gold contact pads.

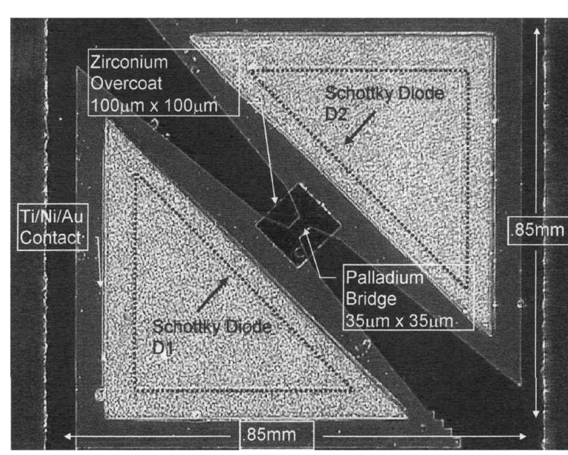

Fig. 5 Complete structure.

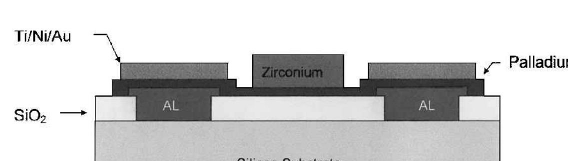

Fig. 6 Schematic side view representation of device.

Fabricated structures had bridge sizes of 15×15 μm, 20×20 μm, 25×25 μm, 30×30 μm, 35×35 μm, and 40×40 μm. Thirty devices of each size were mounted onto standard transistor outline headers with nonconductive epoxy. Silver-filled conductive epoxy was used to form a connection between the header pins and the gold contact pads on the devices. A metal sleeve was welded onto the header to act as a charge holder. Fifty milligrams of zirconium/potassium perchlorate was poured into the sleeve. The pyrotechnic was then consolidated at 15 kpsi and a cup welded over the top of the charge holder to form a hermetic seal. The devices were tested for firing characteristics and ESD insensitivity.

III. Discussion

A lumped-parameter electrical-equivalent model of the device is portrayed in Fig. 7. The structure consists of two diodes $D1$ and $D2$, which are connected, in parallel across the resistance R. The resistance of the silicon substrate was negligible and is therefore not included in the model. A typical I-V characteristic of the series connected diodes is shown in Fig. 8. Actuation of the structure is accomplished by forcing a current to flow through the resistor of sufficient magnitude and duration to evaporate the zirconium overcoat. The Schottky diodes were intentionally fabricated with a breakdown voltage that is slightly higher than the maximum firing voltage induced across the bridge by the firing current. The high breakdown voltage of the diodes ensures that the shunting elements do not affect the firing characteristics of the device. The only purpose of the diodes is to shunt current from an ESD through the substrate, thereby protecting the bridge from transient ESD currents.

Materials that are typically used to construct bowties include metals, such as chromium, nickel or nichrome, or semiconductors, such as silicon.[8,9] These materials are generally heated until they vaporize into plasma. The high-temperature plasma then condenses onto nearby fine grain particles of metal and oxidizer, which results in the pyrotechnic heating to its ignition temperature. The amount of thermal energy transferred to the mix is proportional to the amount of vaporized material, which condenses from the plasma. The larger the amount of vaporous material that condenses, the greater the transfer of thermal energy to the mix.

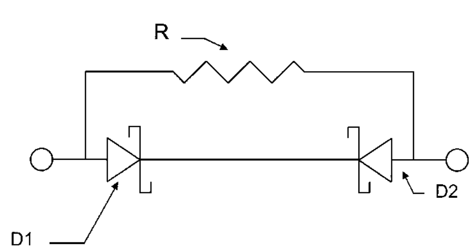

Fig. 7 Equivalent circuit.

The device is initiated by passing a current through the palladium bridge, which results in ohmic heating of the bowtie. To increase the mass of material available for conversion to plasma without altering the resistance of the device, the bridge was overcoated with zirconium. The zirconium makes a poor electrical contact to the palladium and therefore does not significantly influence the overall resistance of the bridge.

This results in the ability to choose the electrical characteristics of the heating element independently of the overcoating material. The bridge element can be fabricated from any material, which provides the correct electrical properties for the chosen geometry. The overcoat material does not even need to be electrically conductive.

The ability of the palladium bridge to initiate zirconium potassium perchlorate (ZPP) was greatly enhanced by the addition of the reactive metal (i.e., zirconium) to the bridge. The visually observed plasma output of the bridge and its ability to ignite a pyrotechnic across an airgap ($\approx$1.25 mm) were significantly increased by this addition.

The composite structure transfers heat via conduction from the palladium bridge to the zirconium overcoat. This allows for a large thermal mass (compared to the uncoated palladium) to be heated until the zirconium vaporizes and forms a plasma. The zirconium layer acts as a source of a reactive metal plasma during ignition, which provides substantial thermal output during firing and allows the structure to promptly initiate ZPP or other ordnance materials (i.e., $BKNO_3$).

Observation of the bridge during firing shows a large plasma event occurring in less than 50 μs or even faster if the bridge is actuated with a current, which significantly exceeds the all-fire level (i.e., function times less than 3 μs have been demonstrated). As the zirconium plasma condenses onto a particle of oxidizer, it assists in generating an exothermic reaction. The result is a more uniform ignition of the mix. Firing data, which substantiates this hypothesis, will be presented later in the paper.

Another advantage of the overcoat is the structural reinforcement it provides to the bridge. The observation was made that rapid heating and cooling of a bare bridge by repeated electrical excitation could eventually lead to cracks as the metal suffered mechanical fatigue and eventual failure.

This tendency was eliminated by the application of the zirconium overcoat. The thick layer of metal composed of the palladium/zirconium laminate is more mechanically robust than just the thin palladium bridge. The bridge is therefore more resistant to fracture caused by thermal and mechanical stress. No cracks were observed in the laminated bridge after repeated excitation with currents slightly less than ($\sim$50 mA) those required to fire the part.

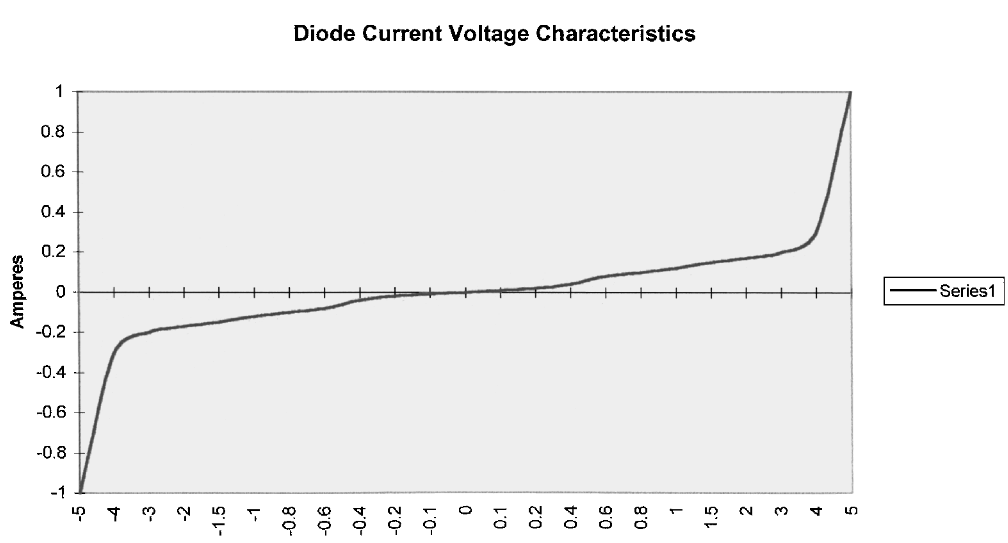

Fig. 8 I-V characteristic of diodes.

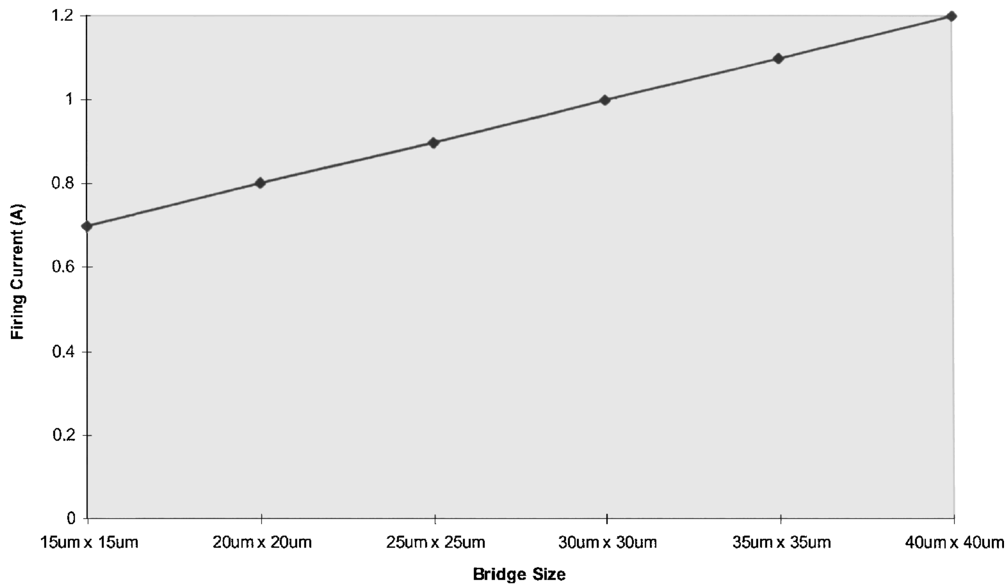

Fig. 9 Firing current vs bridge size.

IV. Firing Results

A series of constant current firing tests were performed on parts to examine the all-fire and no-fire current thresholds. The all-fire level indicates the minimum current that will actuate the device; the no-fire level indicates the maximum current that will not actuate the device. A conventional Bruceton test scheme was used to determine these levels.

The test setup consisted of a constant current source, which was switched, in series with a bridge for 1 ms. Firing events were recorded. The results are portrayed in Fig. 9. The observation is made that the firing current of the devices is directly related to the size (i.e., length × width) of the bowtie. The firing current increases as the size of the device increases. The firing energy Q is calculated as

$$Q = \int_0^T (I^2 * R)\,\mathrm{d}t \qquad (1)$$

where R is the resistance of the bowtie (~2 Ω) and the time period T over which power is integrated is 0.1 ms. (All bridges fired in less than 0.1 ms.) A high-speed digital oscilloscope was used to monitor current flowing through and voltage across the device during firing. The resistance of the device during a firing event was then numerically calculated. The change in resistance during firing was observed to be negligible. The smallest bridge was the most sensitive with a firing energy threshold of 98 μJ and the largest bridge the least sensitive with a firing energy of 288 μJ.

The devices can reliably initiate ZPP with less than 100 μJ of energy. It is also apparent that the firing current scales predictably. The relationship between bridge size and firing current provides the advantage of being able to design and fabricate a device for a specified firing current level. A chronological (prefiring, firing, postfiring) series of photographs illustrating a part being fired with a conventional capacitive discharge unit (2 μF at 30 V) is portrayed in Fig. 10. The bridge element and a significant portion of the overcoat have been evaporated. These photographs provide a qualitative representation of the plasma burst during a firing event.

V. Electrostatic Discharge

The behavior of the devices during ESD events was also investigated. The test circuit is illustrated in Fig. 11. The software package PSPICE was used to simulate what the device experienced during ESD testing.[10] A schematic representation of the lumped parameter PSPICE circuit is shown in Fig. 12. Inductor L2 represents the parasitic inductance of the test set.

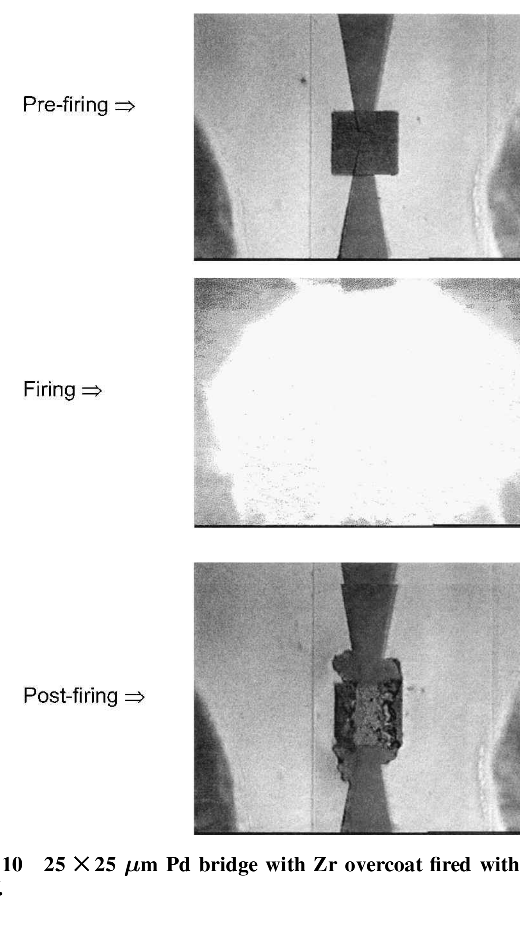

Fig. 10 25 × 25 μm Pd bridge with Zr overcoat fired with 2 uF at 30 V.

Devices with a bowtie size of 35 × 35 μm (with/without shunting diodes) were tested by discharging a 150-pF capacitor (charged to 25 kV) with a 150-Ω resistor in series into one pin of the part while grounding the other pin (i.e., pin to pin). All parts without shunting diodes failed the test and fired.

The discharge was repeated five times per part (with shunting diodes). No deleterious effect (i.e., firing or change in resistance) was noted on any device after any tests. Samples of the 35 × 35 μm device size were then test fired and functioned normally.

Figure 13 illustrates the power and energy coupled to a part with and without shunting diodes in place. The nonlinear characteristics

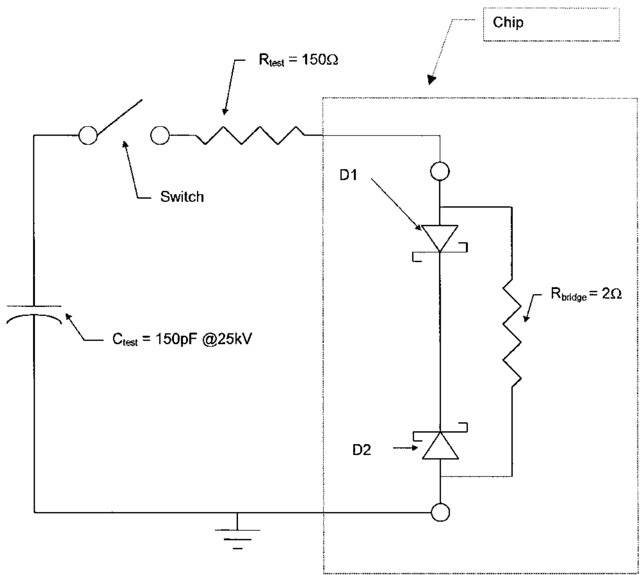

Fig. 11 ESD test circuit.

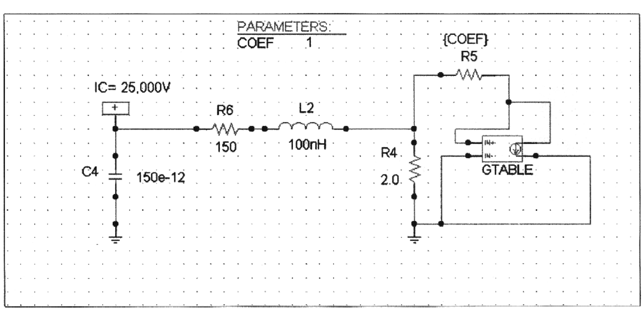

Fig. 12 Schematic representation of PSPICE circuit.

of the diodes shown in Fig. 8 were modeled by the voltage-dependent impedance represented by the PSPICE pseudocomponent GTABLE. The values used to construct GTABLE were determined from numerical measurements on sample devices. The simulation illustrates that the peak power and energy coupled to a part is on the order of 54 kW and 634 μJ for a part without shunting diodes and 3 kW and 10 μJ for a part with shunting diodes. Next generation devices are being fabricated with even higher levels of ESD protection. These devices will allow substantially less ESD current to flow through the bridge and therefore significantly lower the coupled energy during an ESD event.

VI. Design Validation Testing

Design validation tests were run on 612 35 × 35 μm bridges assembled on glass-to-metal headers loaded with consolidated ZPP and hermetically sealed. Three-hundred-and-twenty parts were subjected to the following serial environment after initial resistance, thermal transient, and leak-rate measurements ($<1 \times 10^{-6}$ cc/s at 1 atm He): 1) exposure to high-temperature storage of 144 h at 107°C; 2) thermal shock and humidity—6 cycles between −40 and 107°C with 12 h at each temperature with less than 3-min transition between temperatures (1 cycle = 24 h); and 3) random vibration with temperature per MIL-STD-810 Method S14:4 category I. Three perpendicular axis with 8 h at −40, 21, and 90°C. Broadband g_{rms} in each axis as follows: z axis 2.209 g_{rms}, y axis 1.168 g_{rms}, x axis 0.894 g_{rms}.

Two-hundred-and-twenty parts were not subject to environments and were tested as baseline or preenvironment parts. An additional 72 parts were tested for ESD and 1026 h of monitor current comprising 38 cycles of 27 h duration with each cycle having 8 h at −40, 21, and 90°C.

The environmentally stressed parts and baseline parts were then tested to determine all-fire and no-fire levels plus function time before and after environments. Prior to these tests resistance, thermal transient, and leak rates were again verified. The results of these design validation tests were extremely positive in that parts with <1.2A/1 ms all-fire, >0.5A/10 s no-fire at 99.999% reliability/95% confidence and function time to peak pressure of less than 1 ms were demonstrated as shown in Tables 1 and 2.

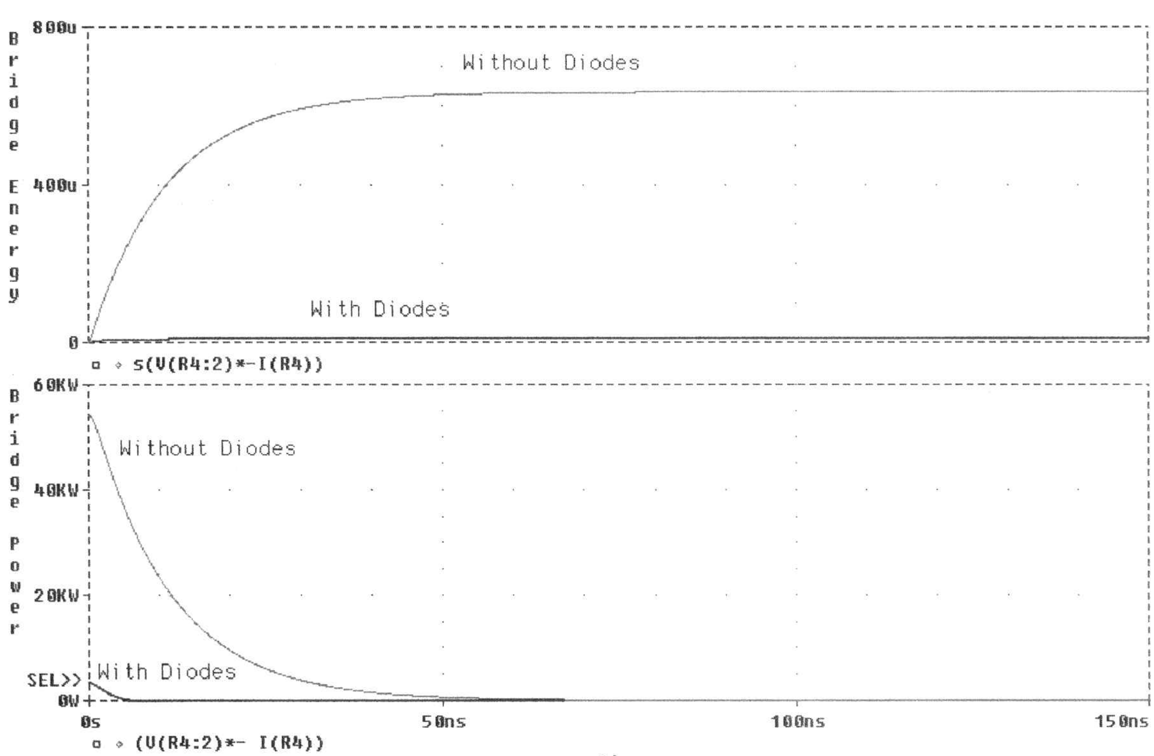

Fig. 13 Power and energy coupled to bridge during ESD event.

Table 1 All-fire (AF)/no-fire summary

Bond/environment/ no environment	AF at 1 ms, 99.999% at 95% confidence −40°C	AF at 1 ms, 99.999% at 95% confidence +21°C	AF at 1 ms, 99.999% at 95% confidence +90°C	AF at 1 ms, 99.999% at 95% confidence +21°C
Wirebond	1.037 A	NA	0.583 A	NA
Wirebond	1.039 A	NA	0.617 A	NA
Conductive epoxy	1.026 A	NA	0.613 A	NA
Conductive epoxy	1.040 A	0.997 A	0.613 A	0.605 A

Table 2 Time-to-peak pressure summary in 10 cc closed bomb at 1.7 A/1 ms

Group	Bond	Mean Time-to-peak output pressure/ mean output pressure temperature = 21°C	Mean time-to-peak output pressure/ mean output pressure temperature = −40°C	Mean time-to-peak output pressure/ mean output pressure temperature = +40°C
Baseline	Wirebond	<0.1 ms/546 psi	<0.1 ms/566 psi	<0.1 ms/605 psi
Post serial environment	Wirebond	<0.1 ms/563 psi	< 0.1 ms/581 psi	<0.1 ms/560 psi
Post ESD	Wirebond	<0.1 ms/575 psi	NA	NA
Post monitor current	Wirebond	<0.1 ms/557 psi	NA	NA
Baseline	Conductive epoxy	<0.1 ms/556 psi	<0.1 ms/547 psi	<0.1 ms/493 psi
Post serial environment	Conductive epoxy	<0.1 ms/539 psi	<0.1 ms/518 psi	<0.1 ms/525 psi
Post ESD	Conductive epoxy	< 0.1 ms/567 psi	NA	NA
Post monitor current	Conductive epoxy	<0.1 ms/invalid	NA	NA

VII. Conclusion

A novel monolithic EED referred to as the CCSCB has been introduced. The device consists of a palladium bridge-heating element, which has been selectively coated with zirconium to enhance ignition of a conventional pyrotechnic mix. Integrated diodes were incorporated into the structure to protect against ESD events. The device has demonstrated low, predictable firing currents and ESD insensitivity. Conventional microelectronic fabrication techniques were used, which allow for very economical, large-volume manufacturing.

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