The Semiconductor Bridge (SCB) Igniter*

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ABSTRACT

We have developed a silicon semiconductor bridge (SCB) igniter which, when driven with a low-energy current pulse, produces a plasma discharge that ignites energetic materials. Our experiments have demonstrated that SCB explosive devices function in a few tens of microseconds at one-tenth the input energy of hot-wire devices. Despite the low input energies for ignition, tests have demonstrated SCB devices to be explosively safe, passing electrostatic discharge (ESD) requirements and no-fire current levels. In fact, SCB devices can have better no-fire characteristics than hot-wire devices, because of the intimate bridge contact between the underlying thermally conductive substrate. We have tested several different prototype explosive devices. In addition, we have tested SCB actuators with breadboarded "smart" firing sets that will fire the SCB actuators only after transmission of a digital code, after a preset delay, or in a preprogrammed sequence.

Keywords: semiconductor bridge, SCB, pyrotechnic igniter, explosives

Introduction

Most explosive devices use small metal bridgewires, or hot wires, to ignite an energetic powder, such as pyrotechnic, primary or secondary explosives, that has been pressed against the bridgewire. Passage of a low current through the wire heats the wire and in turn, the energetic material in a few milliseconds. Hot wires are used in a wide variety of explosive devices including actuators, detonators, and igniters.

We have developed a different method for explosive ignition.[1] This method utilizes a heavily doped polysilicon bridge that is over 30 times smaller in volume than conventional bridgewires. Consequently, the semiconductor bridge, or SCB, can be rapidly heated when driven by a short (less than 20 μs), low energy (as little as 0.03 mJ) current pulse (30 A). In fact, within a few microseconds after the start of the current pulse, the SCB produces a plasma discharge that heats the surrounding energetic material to ignition, obtaining an explosive output in times as short as a few tens of microseconds.[2] Because the SCB is in intimate contact with a thermally conductive substrate, the no-fire capabilities of SCB devices are excellent and can exceed the no-fire current levels of hot-wires. (No fire is defined as the highest current level that can be applied for a period of time, usually 5 minutes, without the device firing; some specifications also require that the device can still function normally after application of the no-fire pulse.) In addition to no-fire safety, we have also demonstrated the electrostatic discharge (ESD) safety of SCB devices.

SCB Processing and Bonding

Figure 1 shows a portion of an SCB die processed from a wafer of polysilicon on silicon. The bridge is formed out of the heavily doped region enclosed by the dashed lines in the figure and has a thickness, t, determined by the depth of the polysilicon layer, a width, W, defined by the shape of the doped region, and a length, L, determined by the space between the aluminum lands. For a one-ohm bridge, 100 μm long × 380 μm wide × 2 μm thick, the polysilicon layer is doped to a concentration greater than 10^{19} phosphorous atoms/cm^3. The processing procedure consists of three steps. The first step

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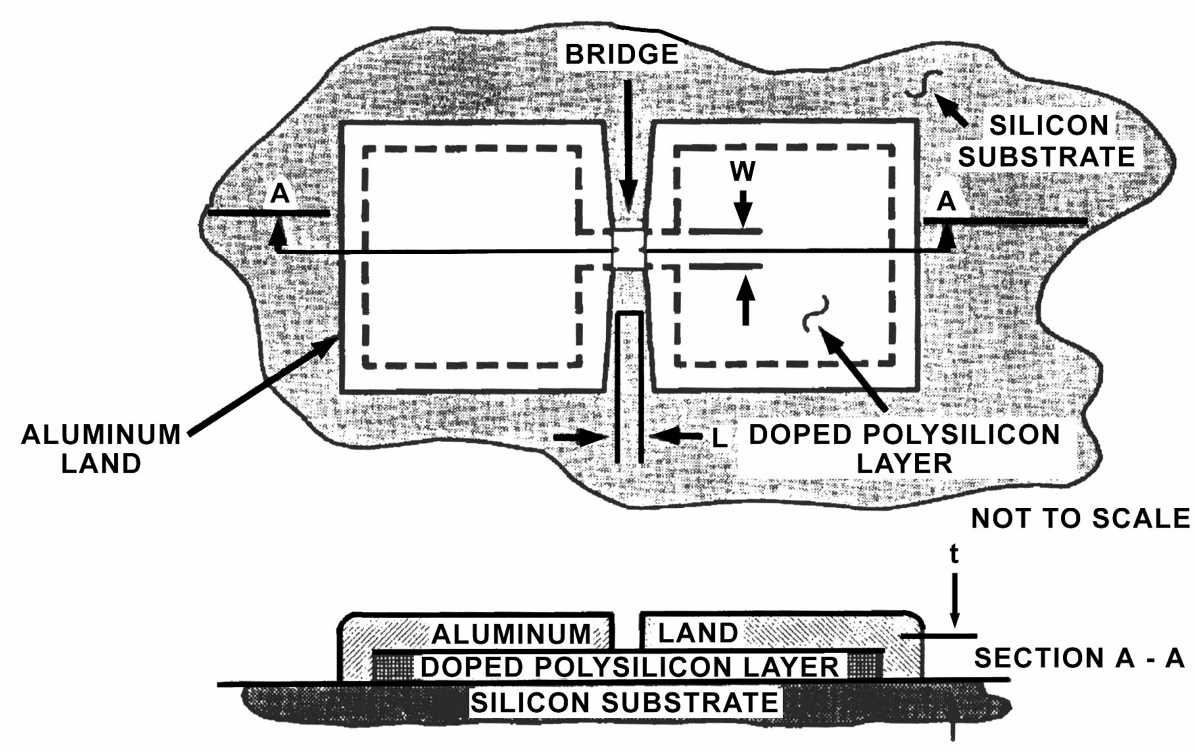

Figure 1. Simplified sketch of a semiconductor bridge (SCB). The bridge is formed out of the heavily doped polysilicon layer enclosed by the dashed lines. Typical bridge dimensions are 380 μm wide (W) by 100 μm long (L) by 2 μm thick (t). Electrical leads are attached to the 2 μm thick aluminum lands, permitting an applied current pulse to flow from land to land through the bridge. The bridge illustrated is designated as a type 3-2 design.

dopes the polysilicon layer, the second defines the n-doped region, and the third defines the lands and the finished bridge. From a single 4 inch wafer over 2000 SCB "chips" can be obtained. We can easily redesign the two masks used for steps two and three to produce SCB geometries that meet particular device requirements. For example, larger bridges have higher no-fire currents but also higher all-fire energies. We have studied many different bridge geometries, each identified by a different type designation [e.g., the rectangular design (100 μm × 380 μm × 2 μm) of the SCB illustrated in Figure 1 is identified as a type 3-2 bridge]. The aluminum lands determine the length of the bridge and also provide a very low contact resistance to the underlying doped polysilicon areas. Aluminum leads are wirebonded to the lands and the metal posts of the header on which the SCB die is mounted. This wirebonding procedure has proved to be quite rugged, capable of withstanding 60 kpsi loading pressures.

SCB Operation

When an SCB is fired in air it produces a bluish colored plasma discharge and an audible "click." Spectroscopic studies of the discharge revealed the plasma to have a blackbody temperature of approximately 550 K. The bridge burn mechanism was determined by high-speed framing photography experiments correlated with the current and voltage waveforms across the SCB. The burn process that produces the plasma discharge proceeds as follows. Application of the current produces a melting and vaporization of portions of the bridge. The process forms a weakly ionized silicon vapor above the bridge and continues until all of the bridge is consumed. Once the bridge is completely melted and vaporized the current transfers to the ionized vapor producing the plasma discharge. Typical current, voltage and impedance waveforms for this process are shown in Figure 2. The initial "bump" in the impedance waveform at 3 µs is the intrinsic/extrinsic transition; the slow rise in impedance between 4 and 11 µs is the bridge vaporization process. The sudden increase in impedance at 11 µs signals the onset of the plasma discharge which is sustained until the current pulse stops. We emphasize here the formation of the plasma discharge and the impedance waveforms, because, one, we have demonstrated that it is the plasma discharge that ignites the powder and, two, we have observed that the shape of the impedance waveform is independent of the voltage or current waveforms (i.e., independent of the firing set).

Hot wire heat transfer is usually modeled as a thermal conductive mechanism dependent on mechanical contact between the wire and the surrounding energetic material. In contrast, our studies indicate that the SCB transfers heat to the energetic material by a process we call a microconvective mechanism. In this hypothesis, we envision the plasma condensing on the energetic material and heating it to the ignition temperature. Based on the fast function times and low energy ignition requirements of SCB devices, we believe this process to be much more efficient than the heat transport mechanism for bridgewires. In contrast to exploding bridgewire (EBW) detonators operating at high voltages, there is not a sufficient plasma shock when SCB's are operated at low voltages to cause shock initiation.

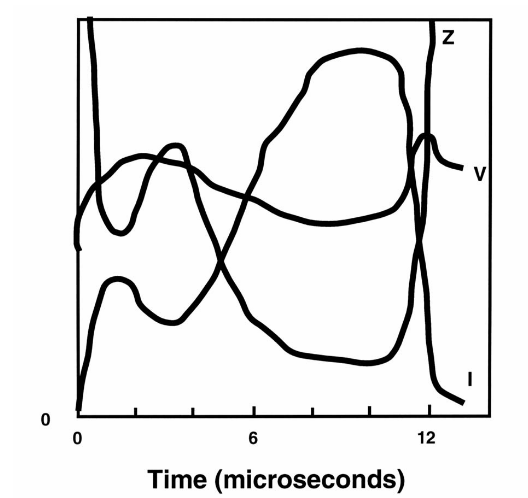

Figure 2. Current, voltage and impedance wave forms across an SCB. The onset of the plasma discharge at 11 µs produces ignition.

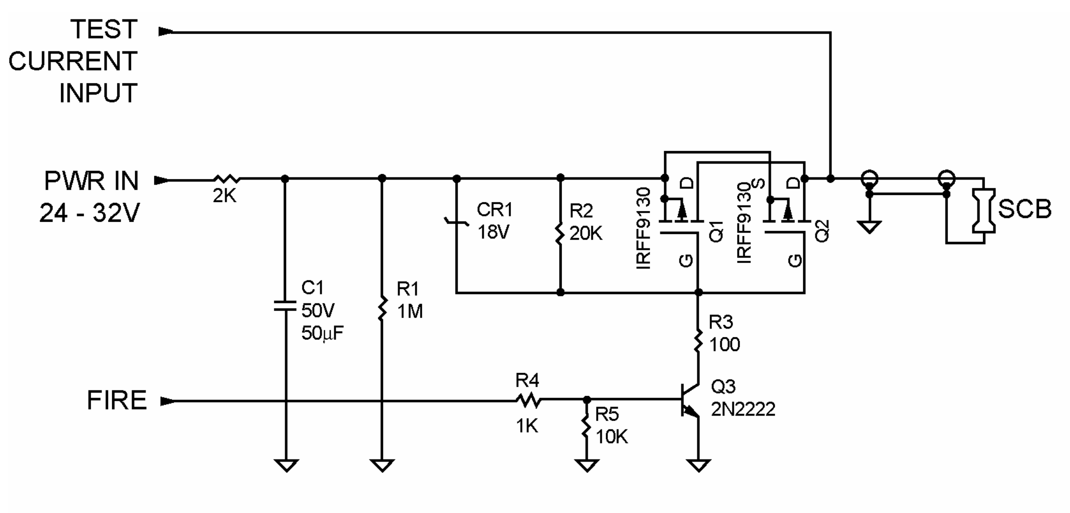

Figure 3. Schematic diagram of a SCB LVCDU firing set.

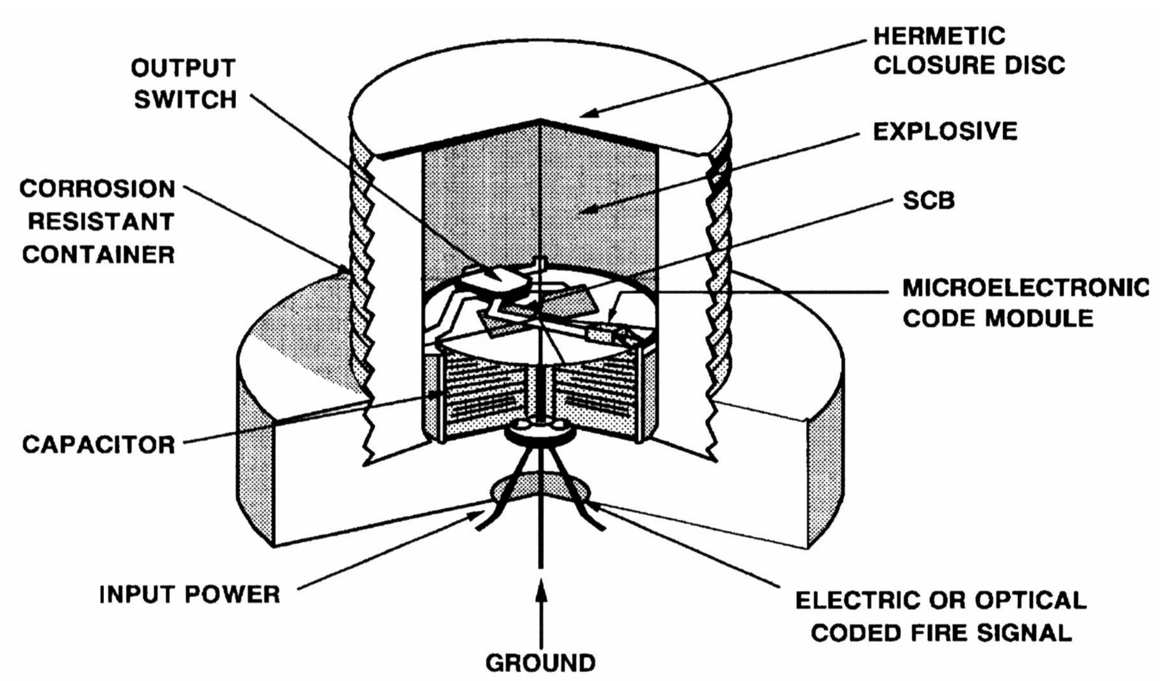

Figure 4. Smart SCB component concept; a thumb-sized, 3-lead device that contains the SCB, explosive powder, switch, capacitor and a microelectronic module used for code identification or delay timing.

Low Voltage Firing Set

We designed a low voltage (24–3 V) capacitor discharge unit (LVCDU) firing set shown schematically in Figure 3. This firing set incorporates fast FET switches, and a low voltage 50 μF capacitor. Typical current and voltage waveforms are shown in Figure 2. The test current input line serves as a continuity test which is used to assure that the SCB device is in place.[3]

Comparison of SCB and Hot-Wire Actuators

A study comparing a hot-wire pyrotechnic ($TiH_{1.68}KClO_4$) actuator with the same actuator slightly modified to accommodate an SCB was conducted.[4] The actuators were assembled using two different SCB die. Fifty units contained type 3-2 die and 50 units contained a type 15 die, same as a 3-2 but with a different land shape (see Ref. 1). All of the actuators underwent three thermal cycles consisting of 5 hours at 74 °C and 4 hours at –54 °C. Twenty unit all-fire and no-fire tests were carried out at –54 and 74 °C, respectively. Ten unit pin-to-pin ESD tests were carried out at ambient temperature for each SCB die design. The data are summarized in Table 1.

Table 1. Comparison of Hot Wire and SCB Devices.

	Hot Wire	Type 3-2	Type 15
All-Fire Energy (mJ)	32.6±1.02 (ambient)	2.72±.48 (–54 °C)	1.33±.03 (–54 °C)
No-Fire Current A	1.1 (ambient)	1.39±.03 (74 °C)	1.30 ±.12 (74 °C)
ESD Test	Passed	Passed	Passed
Function Time(μs)	3400 (ambient)	60 (ambient)	60 (ambient)

This study clearly showed the advantages of SCB devices. Namely, they function at one-tenth the input energy of conventional hot-wire units but based on the no-fire tests are safer than the hot-wire analogs. In addition, SCB devices function in a few tens of microseconds compared to the millisecond response of hot-wire units.

Smart SCB Concept

The smart SCB concept is depicted in Figure 4 and consists of a thumb-sized package that includes the SCB, explosive, fast switch, capacitor and a miniaturized CDU/logic firing set. This device has three inputs, a common, power line and coded signal line; the latter may either be a wire or a fiber optic link. In our first device, after the capacitor was charged, the unit would not function until the correct coded word was transmitted to the device's logic circuit. To improve safety, a second device required two commands; the first permitted the capacitor to charge and the second, if correct, then permitted the SCR to close. If any of the commands in either device were incorrect, the unit would not function.

Summary

We have demonstrated that an SCB can ignite a variety of explosive materials[6] at very low energies but is explosively safe, passing both ESD and no-fire requirements. Indeed, the no-fire current levels for SCB igniters are higher than for hot-wire analogs. While SCB die could be used wherever hot wires are employed this would not take full advantage of the features of SCB igniter. As we discussed, SCB igniters are readily coupled to digital circuits to produce "smart" explosive units. In addition, SCB igniters can be manufactured using cost effective, high throughput assembly techniques. We believe SCB igniters should have many uses in both commercial and military applications.[5]

References

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6) A partial list of SCB ignited materials includes: $TiKClO_4$, $AlKClO_4$, $BBaCrO_4$, Al-CuO, $AlFe_2O_3$, PETN, HMX, CP, BNCP.