CONF-970495--2

Western State Section/The Combustion Institute 1997 Spring Meeting
April 14 & 15, Livermore, California
SAND97-0186C
SAND--97-0186C

Semiconductor Bridge, SCB, Ignition Studies of Al/CuO Thermite†

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ABSTRACT

We briefly summarize semiconductor bridge operation and review our ignition studies of Al/CuO thermite as a function of the capacitor discharge unit (CDU) firing set capacitance, charge holder material and morphology of the CuO. Ignition thresholds were obtained using a brass charge holder and a non-conducting fiber-glass-epoxy composite material, G10. At -18 C and a charge voltage of 50V, the capacitance thresholds were 30.1 µF and 2.0 µF respectively. We also present new data on electrostatic discharge (ESD) and radio frequency (RF) vulnerability tests.

INTRODUCTION

Ignition difficulties exhibited by many thermite compositions result from their high thermal conductivity In particular, hot-wire ignition is especially affected because the temperature rise of the wire is slow and energy transfer from the wire to the thermite is controlled by conduction. Consequently a large mass of material outside of the critical ignition zone is unnecessarily heated before achieving ignition, which increases the amount of energy required from the firing set.

Semiconductor bridges, SCBs, on the other hand, form a plasma discharge in microseconds which rapidly transfers energy via a convective process to the thermite. This produces a high power density in the ignition zone with less energy loss to surrounding materials. Consequently, thermite compositions can be exploited for pyrotechnic igniters without paying an ignition energy penalty by using an SCB. Through proper choice of charge holder and component materials, electrical ignition energies that rival more traditional pyrotechnic igniter compositions can be achieved.

Statistical ignition-data presented in this paper demonstrate these effects and illustrate the performance of the SCB in contact with thermite compositions. We also found that by changing from a metal charge holder to a non-metallic charge holder a significant reduction in ignition energy was achieved. We also present data on electrostatic discharge (ESD) and radio frequency (RF) vulnerability tests for SCB–thermite devices.

†This work was supported by the United States Department of Energy under Contract DE-AC04-94AL8500. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

SEMICONDUCTOR BRIDGE, SCB

Sandia's semiconductor bridge, SCB, has three forms that were patented in 1987[1] and 1990.[2] Devices utilizing the 1987 patent have been incorporated into Sandia systems for the Department of Energy (DOE), for the Department of Defense (DoD), and for commercial systems.[3]

The device described in the 1987 patent is shown in Fig. 1. It consists of a small doped polysilicon (or silicon) volume formed on a silicon (or sapphire) substrate. The length of the bridge is determined by the spacing of the aluminum lands seen in the figure. The lands provide a low ohmic contact to the underlying doped layer. Wires ultrasonically bonded to the lands and the electrical feedthroughs on the explosive header permit a current pulse to flow from land-to-land through the bridge; the ultrasonic process produces very strong bonds and is a cost effective procedure. The doped layer is typically 2 μm thick; bridges are nominally 90 μm long and 270 μm wide. Bridge resistance at ambient conditions is 1 Ω; however, the bridge dimensions can be easily altered to produce other resistances or shapes for specific applications.

A current pulse through the SCB causes it to burst into a bright plasma discharge that heats the exoergic material pressed against the bridge by a rapid and efficient convective process.[4] Consequently, SCB devices operate at input energies typically less than 5 mJ (and as low as 30 μJ). But the SCB devices function very quickly producing an explosive output in less than 60 μs for pyrotechnic devices (where 60 μs is the interval from the firing pulse to the usable explosive output of the device).

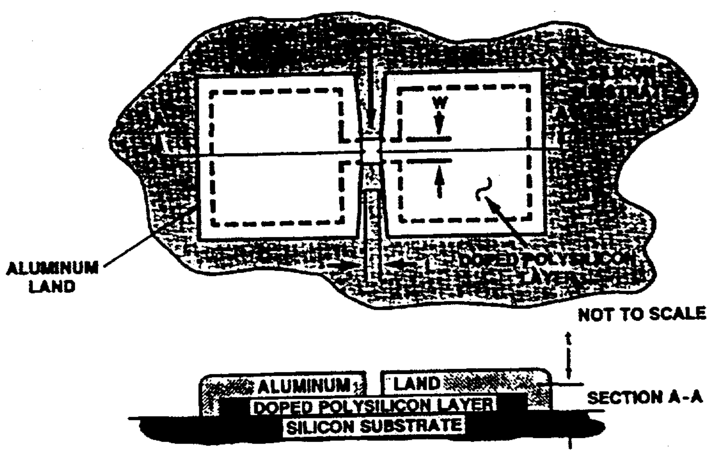

Figure 1. Simplified sketch of a semiconductor bridge (SCB). The bridge is formed out of the heavily doped polysilicon layer enclosed by the dashed lines. The bridge dimensions are 270 μm wide (W) by 90 μm long (L) by 2 μm thick (t). Electrical leads are attached to the aluminum lands, permitting an applied current pulse to flow from land-to-land through the bridge.

Despite the low energy for ignition, the substrate provides a reliable heat sink for excellent no-fire levels. In addition, and as described later the devices are ESD (electrostatic discharge) and RF (radio frequency) tolerant Because the physics of SCB operation is so very much different than for hot wires, SCB devices have both low input energy requirements and high no-fire levels.[5]

EXPERIMENTAL DESIGN

The following is a brief summary of recent experiments to measure the ignition threshold for thermite devices.[6] Type 50B1 SCB die were mounted on standard TO-46 transistor headers; bridge dimensions were 90 μm long and 270 μm wide. For some of the tests the charge holders were brass cylinders pressed and glued onto the TO-46 header.[7] Figure 2 shows a cross section of these devices. The devices were loaded with 184 mg of Al/CuO

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thermite and pressed to a density of 2.3 g/cm³ (45% of TMD). We used spherical, atomized aluminum,[8] and 13600 copper oxide which was commercially processed by air oxidation of fine particle copper.[9]

Our primary goal was to obtain the threshold for ignition as a function of CDU capacitance at a charge voltage of 50 V and with the capacitor and the device both at 0°F. We used the Neyer SENSIT program to determine the capacitor levels and the ASENT program to analyze the data.[10]

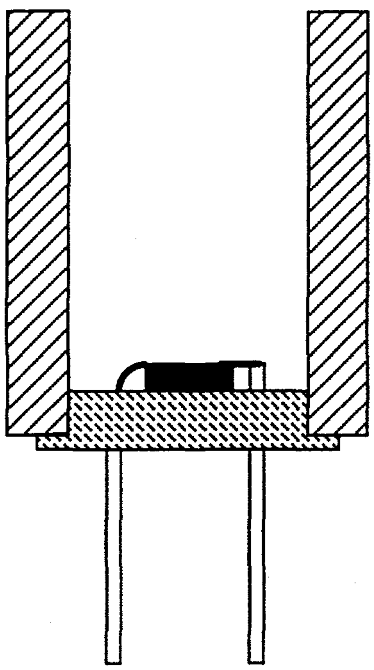

Figure 2. TO-46 transistor base with a brass charge holder. The internal diameter of the charge holder is 0.150" (3.8 mm) and the internal length is 0.270" (6.9 mm). The outside diameter of the charge holder is 0.25" (6.4 mm).

The firing set for these studies was a capacitor discharge unit (CDU) consisting of a capacitor, switched by an SCR, into a series circuit with the SCB and a current viewing resistor, CVR (see Fig. 3). The capacitor was external to the firing set circuit box and was connected to the circuitry with banana plugs; this permitted us to easily change the capacitor. We used ceramic capacitors from AVX Corporation[11] for this study; the capacitances ranged from 1 μF to 40 μF.

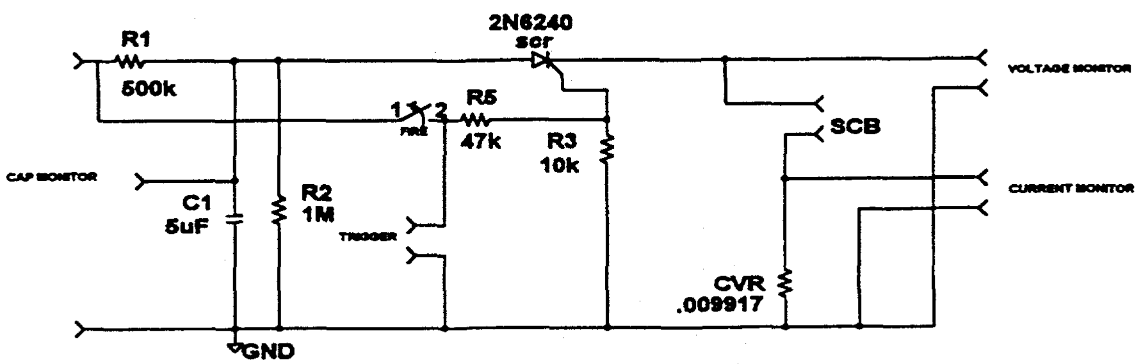

Figure 3. CDU firing set. C1 is the discharge capacitor and is 5 μF in this illustration. Current through the bridge is monitored with the current viewing resistor (CVR). A 5 V, 10 μs trigger fires the switch which can be an SCR as shown or an FET.

In addition to measuring the current, the voltage across the SCB and the CVR was also measured. The waveforms were captured with a Tektronix TDS 640 Digitizer and analyzed with a DEC LSI 11/73 computer system. For each test we calculate the energy delivered by the firing set to the SCB. Function times were obtained by a photodiode that viewed the flash when the unit fired; the times reported are the time interval from the trigger signal to the firing set to the light flash.

First Test Series

Table I. summarizes our first test series. For this 15 unit series the mean all-fire capacitance was 30.1 μF ± 0.2 μF; at a 95% confidence level the 0.999 upper limit was 32.6 μF. Note the small sigma value characteristic of SCB devices

TABLE I: Ignition Data for Brass Charge Holder, Capacitor Voltage of 50 V, Units at 0°F

Capacitor (μF)	Function Time (μs)	Capacitor (μF)	Function Time (μs)	Capacitor (μF)	Function Time (μs)
11.67	No Go	15.36	No Go	19.07	No Go
23.50	No Go	39.2	931	33.0	2328
29.3	No Go	31.9	1352	30.1	No Go
31.9	3514	30.1	2600	29.3	0
30.2	742	29.3	No Go	30.0	No Go

Second Test Series

This test series mirrored the first with the exception that the charge holder was G10, which is a non-electrically conductive, fiber-glass-epoxy composite (see Fig. 4). Again our goal was to determine the threshold capacitance of the CDU firing set at 50 V on the charge capacitor. These tests were all carried out at 0°F. The charge holder was loaded with 200 mg of Al/CuO thermite again pressed to a density of 2.3 g/cm^3. The results are summarized in Table II. Using the SENSIT and ASENT programs we determine the mean all-fire capacitance to be 2.08 μF ± 0.45 μF; at a 95% confidence level the 0.999 upper limit was 6.30 μF.

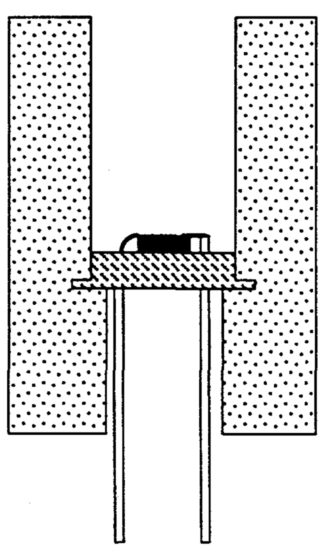

Figure 4. G10 charge holder. The internal diameter is 0.15" (3.8 mm) and the length is 0.36" (9.1 mm).

Table II: Ignition Data for a G10 Charge Holder, Capacitor Voltage of 50 V, and Units at 0°F

Capacitor (μF)	Function Time (μs)	Capacitor (μF)	Function Time (μs)	Capacitor (μF)	Function Time (μs)
15.63	786	11.61	565	7.26	781
1	No Go	4.83	672	3.34	567
2.11	No Go	3.34	626	1	No Go
		2.03	651		

Next we carried out a 10 unit SENSIT study to determine the voltage threshold for a 3.34 μF CDU for units again fired at 0°F. We obtained a mean voltage of 36.76 V ± 0.8 V; at a 95% confidence level the 0.999 upper limit was 4.22 V (see Table III.)

Table III: Ignition Data for a G10 Charge Holder, 3.34 μF CDU Capacitor, and Units at 0°F

Charge Voltage (V)	Function Time (μs)	Charge Voltage (V)	Function Time (μs)	Charge Voltage (V)	Function Time (μs)
32.5	No Go	36.2	No Go	45	846
40.6	651	38.4	1257	35.1	No Go
37.3	No Go	37.8	2513	38.5	843
		36.7	1389		

Third Test Series

The goal of this test series was to measure the ignition threshold at 0°F but with UP 13600 CuO[12] versus the 13600 CuO used for the previous experiments. (The 13600 and UP 13600 are company designations that refer to different processes for preparing the CuO; see references for details.) The aluminum was the same material used previously. The charge holder was the G10 material and was loaded with 200 mg of the new thermite formulation pressed to the same density (2.3 g/cm^3) as in the previous series,. We fired 10 units according to the Neyer program and determined the mean all-fire capacitance to be 2.07 μF; the data were degenerate (no crossover) thus error and confidence limits were not obtained. The data are summarized in Table IV.

Table IV: Ignition Data for UP 13600 CuO, a G10 Charge Holder and a 50 V CDU

Capacitor (μF)	Function Time (μs)	Capacitor (μF)	Function Time (μs)	Capacitor (μF)	Function Time (μs)
4.83	945	3.34	977	2.01	1273
1.17	No Go	1.905	No Go	2.63	1148
1.53	No Go	2.07	No Go	2.27	1141
		1.84	No Go		

We then carried out a 10 unit SENSIT study to determine the voltage threshold for a 3.34 μF CDU for units fired at 0°F. We obtained a mean voltage of 38.4 V; again the data were degenerate. The data are summarized in Table V.

Table V: Ignition Data for UP 13600 CuO, a G10 Charge Holder, and a 3.34 μF CDU Capacitor

Charge Voltage (V)	Function Time (μs)	Charge Voltage (V)	Function Time (μs)	Charge Voltage (V)	Function Time (μs)
32.5	No Go	36.2	No Go	39.9	1532
38.10	No Go	39.0	1422	39.0	No Go
38.6	1590	37.6	No Go	39	2146
		37.8	No Go		

The data for all three test series is summarized in Table VI. The function times and SCB energies reported are the average times for the shots that fired.

TABLE VI: SUMMARY

Shot Nos.	CuO	Cap. Size (μF)	Cap. Volts (V)	Charge Holder	SCB Energy (mJ)	Function Time (μs)
792-806	13600	30.1	50	Brass	28.	2019
941-950	13600	2.1	50	G10	3.1	664
1114-1123	UP 13600	2.1	50	G10	2.3	1097
951-960	13600	3.3	37	G10	1.8	1250
1124-1133	UP 13600	3.3	38	G10	2.2	1673
963	13600	8.7	25	G10	1.7	841
1134	UP 13600	8.7	25	G10	1.8	No Go
962	13,600	19.3	20	G10	1.6	784
1135	UP 13600	19.3	20	G10	1.7	1343
961	13600	19.3	17	G10	1.6	No Go
1136	UP 13600	19.3	17	G10	1.5	No Go
940	13600	19.3	50	G10	3.9	629
1111	UP 13600	19.3	50	G10	4.5	957
1110	UP 13600	3.35	50	G10	3.4	1262

Note: Shots *940*, *1110* and *1111* used room temperature units; all other tests were at 0°F.

Fourth Test Series

Based on the previous results, Energetic Materials Associates, Inc. designed and built components for their commercial applications. Units were sent to Sandia for testing in ESD and RF environments.

The Sandia Standard Man ESD test places the unit under test in series with a 500 Ω resistor and a 600 pF capacitor. The capacitor is charged to 20 kV and then discharged through the unit and 500 Ω resistor using a fast rise-time switch. We tested units at 20, 15 and 10 kV. The applied pulses were pin-to-pin, that is the current pulse was through the SCB as opposed to a pin-to-case test. We also submitted 2 units to the standard DoD ESD test. For the DoD tests the units are in series with a 5000 Ω resistor and a 500 pF capacitor charged to 25 kV. The results are summarized in Table VII. None of the units fired when subjected to the ESD pulses. However the Standard Man test at 20 and 15 kV did damage the bridge as indicated by the change in resistance.

All of the units were fired using a 10 μF firing set charged to 45 V. All but one of the units functioned properly. However, the current waveform for the no-fire indicated that the unit was not loaded properly; the unit will be dissected and examined to determine the cause of the no fire.

TABLE VII: ESD TESTS

Type	Voltage (kV)	Resistance before test (Ω)	Resistance after test (Ω)	Function Go/NoGo
G10	20	1.018	9.54	Go
G10	20	1.001	10.91	Go
G10	15	1.008	2.089	Go
G10	10	1.007	1.010	Go
Steel	20	1.012	7.396	Go
Steel	20	1.049	4.621	Go
Steel	15	1.015	1.642	Go
Steel	10	1.026	1.016	NoGo

Two of the steel units were injected with 1 Watt of RF power at 10 MHz input frequency for 5 minutes. The resistances of the units increased slightly after the RF injection but none of the units functioned (see Table VIII). A third units was subjected to 2, 3, 4 and 5 watt injections, each 5 minutes long; again the unit did not fire.

The two units tested at 1 Watt were fired using the 10 μF, 45 V firing set and functioned properly (Table VIII). The third unit was not tested but will be opened and examined to determine if the RF injection caused any damage to the bridge or the powder interface.

TABLE VIII. RF TESTS

Type	RF Power (W)	Resistance before Test (Ω)	Resistance after Test (Ω)	Function Go/NoGo
Steel	1	1.205	1.255	Go
Steel	1	1.150	1.198	Go
Steel	2	1.322	1.308	
(repeat)	3	1.308	1.378	
(repeat)	4	1.378	1.346	
(repeat)	5	1.346	1.335	

SUMMARY

The mean all-fire thresholds for these devices were significantly influenced by the type of the holder. The all-fire capacitance for the G10 units (at 50 V) was approximate one-tenth that of the capacitance for the brass units. The reduction in threshold capacitance may be due to the thermal losses at the metal charge holder or, based on comparisons of the current and voltage waveforms, may also be due to the effect on the plasma of the ground plane provided by the brass cylinder. Operation with the G10 header at 50 V and with a 3 to 6 μF capacitor provides for a large margin for reliable device function. Powder morphology affects function time but not ignition sensitivity. The 13600 material produced an output approximately 1.5 times faster than the UP 13600 CuO. All of the units survived ESD and RF injection and all but one of the units functioned properly when fired using a 10 μF 45 V firing set.

ACKNOWLEDGMENTS

This work was sponsored by Sandia's Technical Assistance Small Business Initiative. Our thanks to SCB Technologies Inc. for supplying the G10 charge holders.

For additional information about SCB technology, please contact Bob Bickes, Sandia National Laboratories, (505)844-0423 or rwbicke@sandia.gov.

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[8] Valimet Inc., Stockton, California, H-3 material with a mean diameter of 3.8 μm.

[9] American Chemet Corp., Deerfield, Illinois, type 13600 copper oxide is prepared by air oxidation of fine copper particles.

[10] B. T. Neyer, "More Efficient Sensitivity Testing," EG&G Mound Applied Technologies, MLM-3609, (October 20, 1989).

[11] AVX Corporation, X7R Type, Myrtle Beach, South Carolina.

[12] American Chemet Corp., Deerfield, Illinois, type UP 13600 copper oxide is processed using a proprietary procedure to obtain CuO from precipitated $CuCO_3$.