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Pin-to-pin Electrostatic Discharge Protection for Semiconductor Bridges

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Pin-to-pin Electrostatic Discharge Protection for Semiconductor Bridges

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Abstract

The lack of protection for semiconductor bridges (SCBs) against human electrostatic discharge (ESD) presents an obstacle to widespread use of this device. The goal of this research is to protect SCB initiators against pin-to-pin ESD without affecting their performance. Two techniques were investigated. In the first, a parallel capacitor is used to attenuate high frequencies. The second uses a parallel zener diode to limit the voltage amplitude.

Both the 1 µF capacitor and the 14 V zener diode protected the SCBs from ESD. The capacitor provided the best protection. The protection circuits had no effect on the SCB's threshold voltage. The function time for the CP-loaded SCBs with capacitors was about 11 µs when fired by a firing set charged to 40 V. The SCBs failed to function when protected by the 6 V and 8 V zeners. The 51 V zener did not provide adequate protection against ESD.

The parallel capacitor succeeded in protecting SCB initiators against pin-to-pin ESD without affecting their performance. Additional experiments should be done on SCBs and actual detonators to further quantify the effectiveness of this technique. Methods for retrofitting existing SCB initiators and integrating capacitors into future devices should also be explored.

Acknowledgment

The authors thank K. D. Marx of the Reliability of Electrical Systems Department (Organization 8205) for providing a revised SCB PSpice model.

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Nomenclature

AC	alternating current
BNCP	tetraamine-cis-bis (5-nitro-2H-tetrazolato-N^2) cobalt III perchlorate
CDU	capacitive discharge unit
CP	cyanotetrazolatopentaamine cobalt III perchlorate
EED	electro-explosive device
ESD	electrostatic discharge
HE	high explosive
SCB	semiconductor bridge
V_z	zener breakdown voltage
?	frequency (radians/second)

1. Introduction

Several techniques have been developed to protect electro-explosive devices (EEDs) against radio-frequency interference and electrostatic discharge (ESD) [1-6]. However, the lack of protection for semiconductor bridges (SCBs) against human ESD, as modeled by Fisher [7], still presents an obstacle to widespread use of this device. The goal of this research is to protect SCB initiators against pin-to-pin ESD without affecting their performance. Two techniques were investigated. In the first, a parallel capacitor is used to attenuate high frequencies. The second uses a parallel zener diode to limit the voltage amplitude. This report presents a theoretical analysis, simulation and experimental results, and concludes with a recommendation for future work.

2. Theoretical Analysis

Consider the circuit shown in Fig. 1. This represents an SCB, with resistance R, in parallel with a capacitor, C, being driven by a current source, i(t). The frequency response of this circuit can be determined using steady-state alternating current (AC) analysis, as shown in Fig. 2. At low frequencies, that is $w << \frac{1}{RC}$, the capacitor impedance is much greater than R, so the source current flows through the SCB. Conversely, at high frequencies, that is $w >> \frac{1}{RC}$, the capacitor impedance is much smaller than R, so the source current flows through C. Thus, R and C form a low-pass filter. The design objective, then, is to select C so that it will shunt away the higher frequency ESD current and pass the lower frequency firing set current. Consequently, a 1 µF capacitor was chosen. This capacitor, in parallel with a 1 O SCB, should produce a delay on the order of 1 µs.

Now consider the circuit shown in Fig. 3. For i(t) = 0, the zener diode, D, will conduct when v(t) exceeds the zener breakdown voltage, V_z. The design objective in this case is to select V_z high enough to keep D off during the lower, longer firing set current, yet low enough to turn D on during the higher, shorter ESD current. Consequently, a 14 V zener diode was chosen. Protection can be provided in both directions by replacing D with a pair of back-to-back zener diodes connected in series.

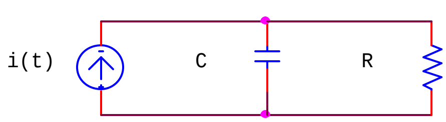

Figure 1. SCB with capacitor.

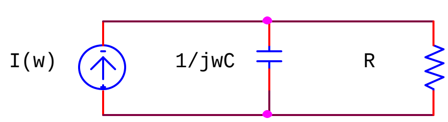

Figure 2. Circuit in frequency domain.

3. Simulation Results

PSpice was used to simulate ESD and function testing of a protected and unprotected 1 O SCB, as shown in Figs. 4 and 5, respectively. The Fisher ESD model is used in this circuit along with a 40 V, 50 µF capacitive discharge unit (CDU). The schematic also includes U22, an SCB model developed by Marx [8,9]. The SCB current waveforms in Fig. 6 indicate that the zener diode, D25, does very little to protect the SCB. However, the capacitor, C5, shunts virtually all of the current away from the SCB. The SCB current waveforms in Fig. 7 indicate that the zener diode has very little effect on the functioning of the SCB. The capacitor, however, appears to delay functioning of the SCB by about 1 µs, as expected.

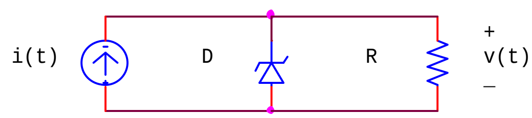

Figure 3. SCB with zener diode.

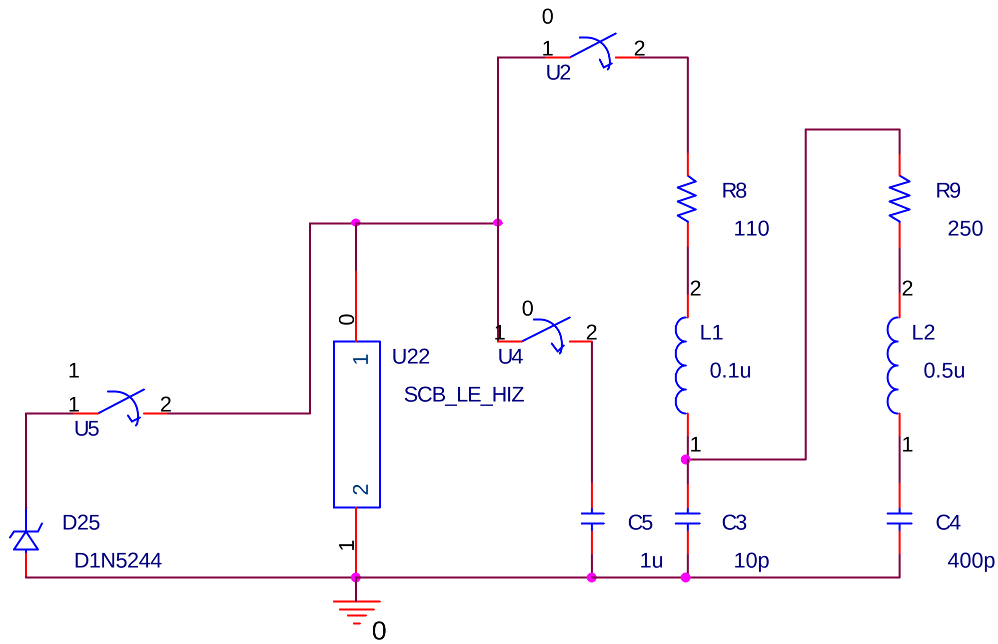

Figure 4. Schematic for simulating ESD testing of SCB with and without protection.

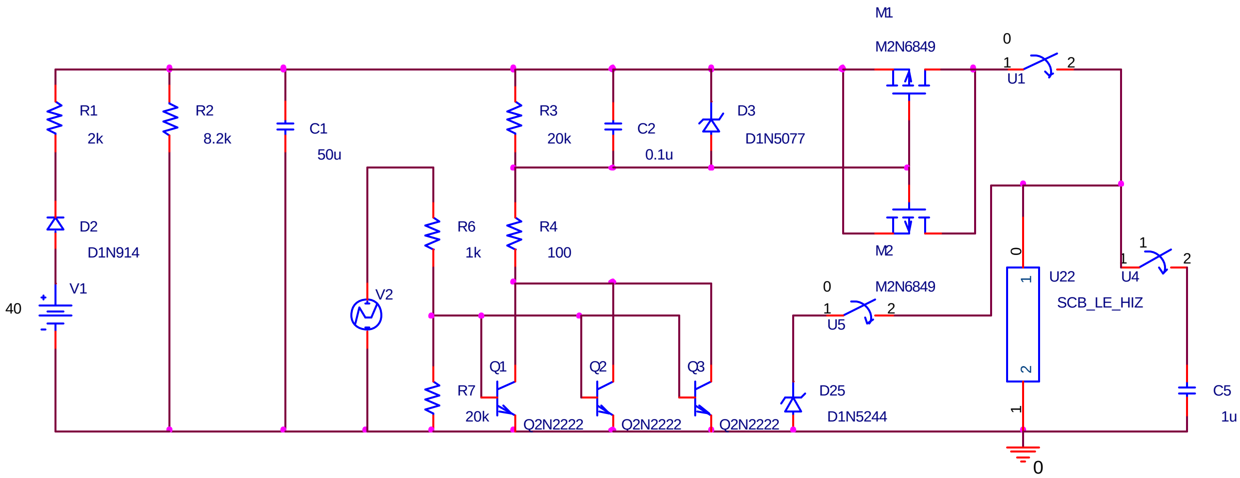

Figure 5. Schematic for simulating function testing of SCB with and without protection.

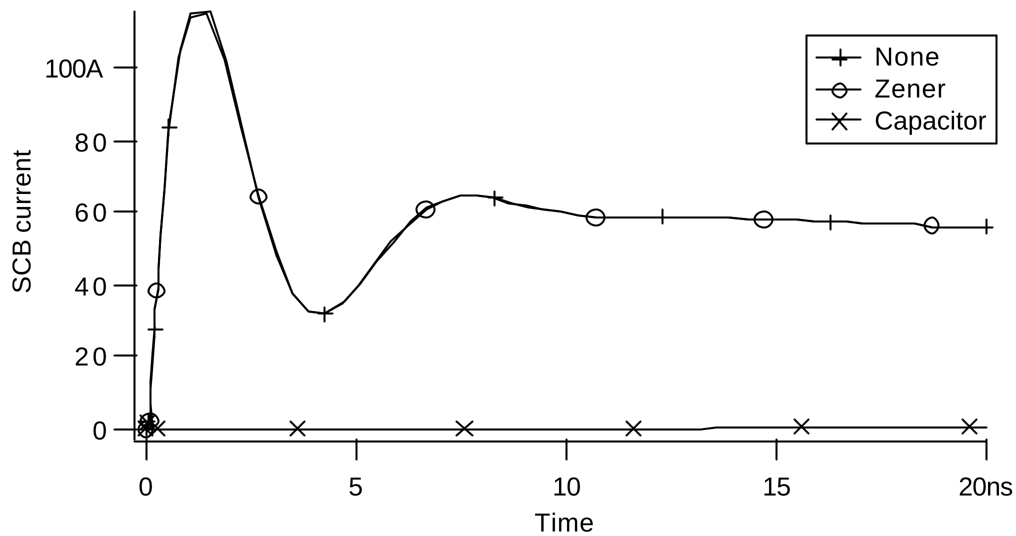

Figure 6. Simulated SCB currents during ESD.

4. Experimental Results

Function and ESD experiments were performed with and without a high explosive (HE) as illustrated in Fig. 8. Table 1 lists the equipment used. The SCBs were connected to the CDU by a 65 ft. C cable and to the ESD tester by custom-made test fixtures.

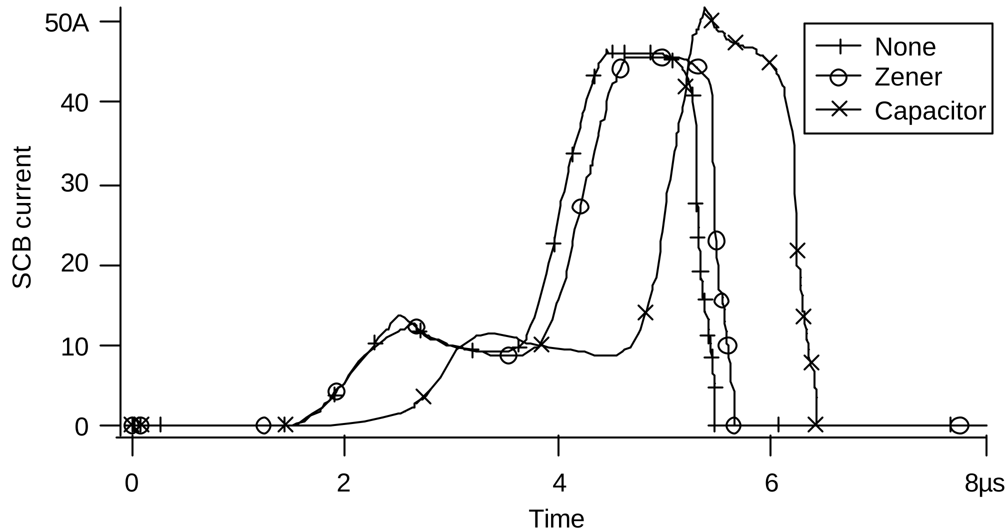

Figure 7. Simulated SCB currents during functioning.

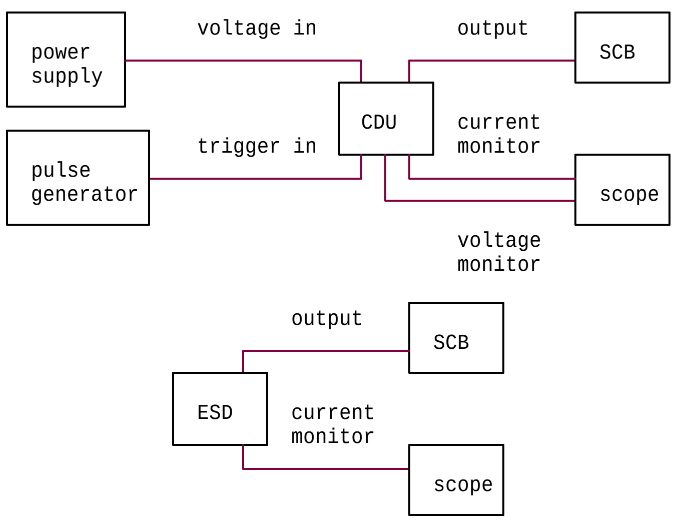

Figure 8. Experimental setups.

Table 1. Equipment list.

Item	Part #	Manufacturer
SCBs	SCB32B1	SCB Technologies
SCBs	SCB50B1	SCB Technologies
SCBs	SCB32B50	SCB Technologies
SCB detonator	X2-300420-1	Pacific Scientific
6 V zener diodes	S6Z/T3-SG	SCB Technologies
8 V zener diodes	S8Z/T3-SG	SCB Technologies
14 V zener diodes	S14Z/T3-SG	SCB Technologies
51 V zener diodes	1N5262B	Vishay
1 µF, 50 V ceramic capacitors	MALCK06BX105K	Mallory
Fisher ESD tester	PT3689	SNL
CDU	1A0662	SNL
Firing set	Prototype	SNL
Power supply (no HE)	PS505	BelMERIT
Power supply (HE)	3006B	Protek
Pulse generator (no HE)	6200	Picosecond Pulse Labs
Pulse generator (HE)	214B	Hewlett Packard
Oscilloscope	TDS 784A	Tektronix
Ohmmeter	4314A	Valhalla

4.1 ESD Tests

The objective of these tests was to determine whether the capacitor or zener diode would protect SCBs against ESD. For no HE, three different SCBs were tested with and without a capacitor. Table 2 indicates that the protected SCBs exhibit negligible resistance change compared to the unprotected SCBs.

Tests were then performed using SCB32B1s loaded with cyanotetrazolatopenta-amine cobalt III perchlorate (CP) or tetraamine-cis-bis (5-nitro-2H-tetrazolato-N^2) cobalt III perchlorate (BNCP) and protected by capacitors or zener diodes with 6 V = V_z = 51 V. None of the protected SCBs were initiated by the ESD pulse, as shown in Table 3. The capacitor appears to provide the greatest protection, producing the smallest resistance change. In general, the protection provided by the diodes decreases with increasing V_z, as expected.

Finally, a third series of ESD tests was performed on CP-loaded SCB32B1s protected by a capacitor or 51 V zener. Table 4 indicates that none of the SCBs fired when protected by the capacitor. However, with the zener, 33% of the SCBs fired after the first ESD exposure and they all fired after the second exposure. Consequently, the 51 V zeners were eliminated from further consideration.

Table 2. ESD test with and without capacitor and no HE.

SCB Type	Capacitor	R_I(O)	R_F(O)	?R(O)
SCB32B1	Yes	1.064	1.068	0.004
SCB32B1	Yes	1.064	1.072	0.008
SCB50B1	Yes	1.024	1.025	0.001
SCB50B1	Yes	0.998	0.996	-0.002
SCB32B50	Yes	61.9	61.9	0
SCB32B50	Yes	62.2	62.2	0
SCB32B1	No	1.090	0.910	-0.18
SCB50B1	No	1.009	6.470	5.461
SCB50B1	No	1.027	6.221	5.194
SCB32B50	No	63.9	64.7	0.8

Table 3. SCB32B1 ESD test with protection and HE.

Explosive	Protection	R_I(O)	R_F(O)	?R(O)
BNCP	Capacitor	1.100	1.106	0.006
BNCP	6 V Zener	1.070	1.085	0.015
BNCP	8 V Zener	1.106	1.118	0.012
BNCP	14 V Zener	1.104	1.120	0.016
CP	Capacitor	1.099	1.101	0.002
CP	6 V Zener	1.101	1.105	0.004
CP	8 V Zener	1.063	1.067	0.004
CP	14 V Zener	1.095	1.123	0.028
CP	51 V Zener	1.097	2.562	1.465
CP	51 V Zener	1.077	2.830	1.753

Table 4. CP-loaded SCB32B1 ESD test with protection.

Shot #	Protection	Fired	Comments
1	51 V Zener	No	
2	51 V Zener	Yes	Same zener as shot 1
3	51 V Zener	No	
4	51 V Zener	Yes	Same zener as shot 3
5	51 V Zener	Yes	
6	51 V Zener	No	
7	51 V Zener	Yes	Same zener as shot 6
8	51 V Zener	Yes	
9	51 V Zener	No	
10	Capacitor	No	
11	Capacitor	No	
12	Capacitor	No	
13	Capacitor	No	
14	Capacitor	No	
15	Capacitor	No	
16	Capacitor	No	
17	Capacitor	No	
18	Capacitor	No	

4.2 Threshold Voltage Tests

The objective of these tests was to determine what effect the protection circuits have on the SCB32B1 threshold voltage. For no HE, the threshold voltage is defined as the CDU voltage required to burst the SCB. The Neyer statistical program was employed to determine threshold voltages using experimental data. Table 5 shows that the mean threshold voltage remains unchanged at 18.5 V for the capacitor and 14 V zener. Figure 9 shows the output currents with the CDU charged to 24 V. The 6 V and 8 V zeners were eliminated from further consideration because they prevented the SCB from firing, even with the CDU charged to 40 V.

For CP and BNCP, the SCBs functioned at 15 V but not at 10 V with and without the capacitor or 14 V zener. Therefore, the protection circuits had no noticeable effect on the threshold voltage.

A third threshold voltage test was performed using a 30 µF firing set and CP-loaded detonators with parallel capacitors. These protected detonators were exposed to ESD prior to testing. The data in Table 6 imply a mean threshold voltage of 17.7 V with a standard deviation of 2.6 V.

Finally, a fourth threshold voltage test was performed using the 30 µF firing set and CP-loaded SCB32B1s with no protection and no prior exposure to ESD. The data, shown in Table 7, indicate a mean threshold voltage of 15.6 V with a standard deviation of 2.3 V.

Table 5. Threshold voltage test with and without protection and no HE.

V_{in} (V)	Fired
10	No
15	No
15	No
17	No
18	No
19	Yes
20	Yes
22	Yes
24	Yes
24	Yes

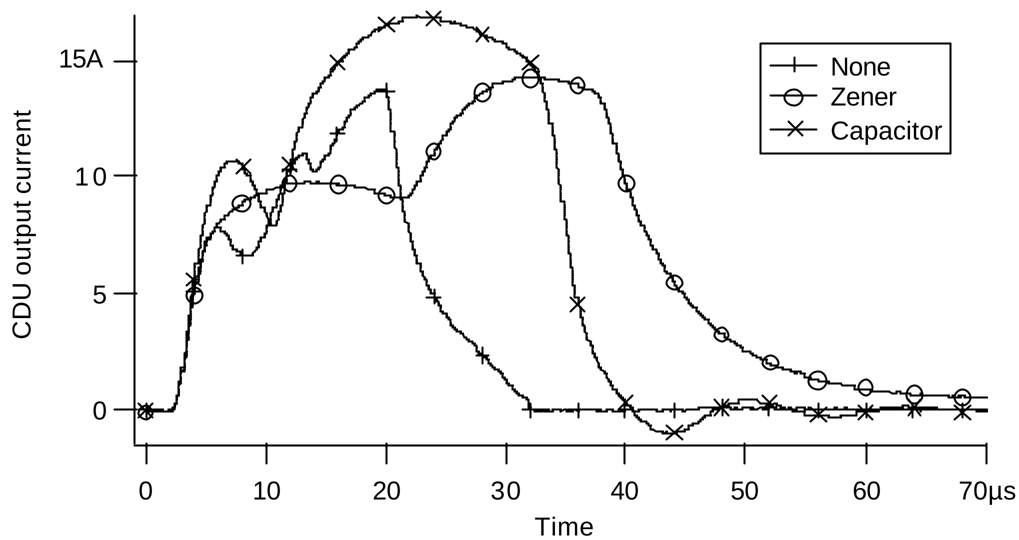

Figure 9. CDU output currents with no HE.

Table 6. CP-loaded detonator threshold voltage test with capacitor.

Vin (V)	Fired
15.500	No
15.750	No
16.000	No
16.250	No
16.500	Yes
16.750	No
17.000	Yes
17.500	No
17.500	Yes
18.000	Yes
20.000	Yes
20.000	No
20.000	Yes

Table 7. CP-loaded SCB32B1 threshold voltage test without protection.

Vin (V)	Fired
13.750	No
14.851	No
15.391	No
15.400	No
15.669	No
15.700	Yes
15.700	Yes
15.750	Yes
15.800	Yes
15.938	Yes
15.940	Yes
16.689	Yes
17.000	Yes
17.000	No
17.441	No
18.130	Yes
22.500	Yes

4.3 Function Tests

The objective of these tests was to determine the function time of the SCB-capacitor combination. A function test was performed using the 30 µF firing set and CP-loaded detonators with parallel capacitors. These protected devices were previously exposed to ESD. The firing set was charged to 40 V. The data in Table 8 imply a mean function time of 10.5 µs with a standard deviation of 0.7 µs.

A second function test was performed using the 30 µF firing set and CP-loaded SCB32B1s with no protection both with and without prior exposure to ESD. The firing set was again charged to 40 V. The data, shown in Table 9, indicate a mean function time of 11.3 µs with a standard deviation of 0.3 µs.

5. Conclusion

Both the 1 µF capacitor and the 14 V zener diode protected the SCBs from ESD. The capacitor provided the best protection. The protection circuits had no effect on the SCB's threshold voltage. The function time for the CP-loaded SCBs with capacitors was about 11 µs when fired by the 30 µF firing set charged to 40 V. The SCBs failed to function when protected by the 6 V and 8 V zeners. The 51 V zener did not provide adequate protection against ESD.

The parallel capacitor succeeded in protecting SCB initiators against pin-to-pin ESD without affecting their performance. Additional experiments should be done on SCBs and actual detonators to further quantify the effectiveness of this technique. Methods for retrofitting existing SCB initiators and integrating capacitors into future devices should also be explored.

Table 8. Function times for CP-loaded detonator with capacitor.

Function time (µs)	ESD tested
11.595	Yes
9.841	Yes
9.881	Yes
10.208	Yes
10.785	Yes
10.457	Yes

Table 9. Function times for CP-loaded SCB32B1 without protection.

Function time (µs)	ESD tested
10.882	Yes
11.559	Yes
10.704	Yes
11.566	No
11.196	No
11.501	No
11.397	No

References

1. H. Frasch, R. Bentley and D. Nelson, "Application of Low-Cost Commercial Technologies for HERO and 300 kV ESD Protection of the 2.75-Inch Rocket Ignition System," *JANNAF Propulsion Meeting*, (December 1996).

2. J. H. Henderson and T. A. Baginski, "An RF-Insensitive Hybrid Electroexplosive Device Incorporating an Integral Filter," *IEEE Transactions on Industry Applications*, **32**,2, 465-470, (March/April 1996).

3. T. A. Baginski and A. S. Hodel, "The Semiconductor Junction Igniter: A Novel RF and ESD Insensitive Electro-Explosive Device," *IEEE Transactions on Industry Applications*, **29**,2, 412-418, (March/April 1993).

4. K. E. Willis, "Methods of Protecting Electro-Explosive Devices from the Effects of RF Radiation and ESD," *33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, (July 1997).

5. R. W. Bickes, Jr., D. E. Wackerbarth, C. B. McCampbell and R. L. Brown, "CAD Devices Protected with SCB Igniters," Sandia National Laboratories report SAND96-1991A, 1996.

6. S. Harris, M. Grubelich, R. Bickes, Jr., R. Brown and C. McCampbell, "An Overview of New Semiconductor Bridge Applications," Sandia National Laboratories report SAND96-2146A, 1996.

7. R. J. Fisher, "The Electrostatic Discharge Threat Environment Data Base and Recommended Baseline Stockpile-To-Target Sequence Specifications," Sandia National Laboratories report SAND88-2658, November 1988.

8. K. D. Marx, R. W. Bickes, Jr. and D. E. Wackerbarth, "Characterization and Electrical Modeling of Semiconductor Bridges," Sandia National Laboratories report SAND97-8246, March 1997.

9. K. D. Marx, D. Ingersoll and R. W. Bickes, Jr., "Electrical Modeling of Semiconductor Bridge (SCB) BNCP Detonators with Electrochemical Capacitor Firing Sets," Sandia National Laboratories report SAND98-0137C, 1998.

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