

PULSE EVALUATION OF HIGH VOLTAGE SiC DIODES

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Abstract

The U. S. Army Research Laboratory (ARL) is evaluating silicon carbide switches and diodes to determine the range of high power and pulsed power applications for which SiC is a sensible material to use. This study focused on 6 kV, SiC P-i-N diodes which were designed by Cree Inc. and packaged and pulse tested at ARL. Diodes were pulsed at a single shot rate both individually and in parallel. Individual diodes were pulsed as high as 5.9 kA (corresponding to an action of $4.5 \times 10^3 \text{ A}^2\text{s}$) for 25 single shots before failing, and as high as 5.0 kA (with an action of $3.5 \times 10^3 \text{ A}^2\text{s}$) for over 100 shots without failure. Five diodes paralleled in the pulse testbed carried a total current of 23 kA with each diode sharing 19-21% of the total peak current. Eight diodes in parallel reached over 39 kA peak current. The ultimate goal is to combine 8-10 diodes in a single, compact package for higher current applications.

I. INTRODUCTION

Army survivability and lethality applications require compact, high power switches that can deliver current at a range of different pulse widths, amplitudes and rise times. In the pulse switch test beds, diodes are typically used to protect other components by clamping negative current or otherwise steering current flow. ARL is investigating SiC P-i-N diodes as a possible replacement for “hockey-puk” silicon diodes. The small SiC diode chips would be combined into modules that could easily be integrated with modules of Si or SiC GTOs. [1, 2] With SiC's tolerances for high temperatures and high current densities, compact modules of SiC diodes might be ideal for protecting other high power circuit components under pulse conditions. The attractive qualities of SiC include a wide energy band gap (3.26 eV), high breakdown electric field ($2.2 \times 10^6 \text{ V/cm}$), high thermal conductivity (3.0 W/cmK) and high saturated electron drift velocity ($2.0 \times 10^7 \text{ cm/s}$). [3] The objectives of this study were to determine what pulse current these SiC diodes could handle over a pulse duration of hundreds of microseconds and how well they would share current when arranged in parallel.

The diodes evaluated in this study were fabricated by Cree, Inc. They are rated for 6 kV blocking and 50 A of continuous forward current. Each diode has a footprint area of about 0.73 cm^2 and an anode area of 0.49 cm^2 . A photo of one diode chip can be seen in Figure 1, with a diagram of the cross section in Figure 2.

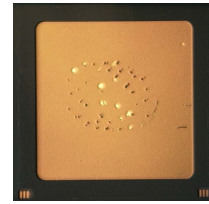


Figure 1. Photo of 8.5 mm x 8.6 mm SiC P-i-N diode. The anode contact is shown, and the cathode contact is on the underside.

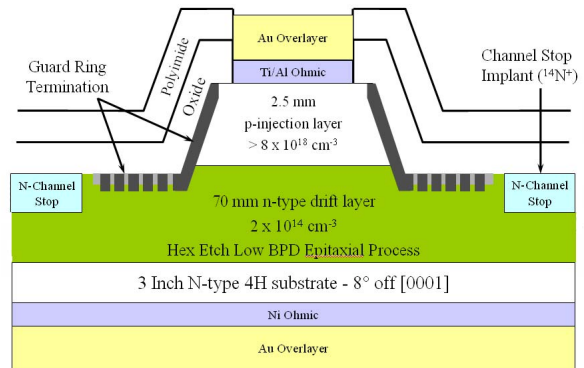


Figure 2. Cross section of SiC diode.

Diodes were individually packaged at ARL prior to pulsing. Copper tabs were soldered to the anode and cathode, and each diode was then encased in epoxy to prevent high voltage flashover. Forward voltage drop and reverse high voltage blocking were verified using a curve tracer and bench-top high voltage supply. Typical I-V curves provided by Cree are shown in Figures 3 and 4.

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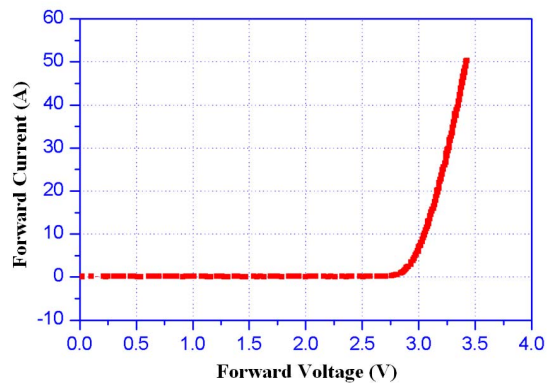


Figure 3. Typical forward voltage drop (measured).

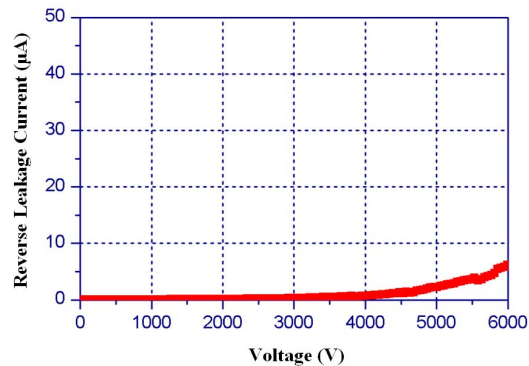


Figure 4. Typical reverse blocking (measured).

II. SINGLE DEVICES

A. Procedure

Diodes evaluated individually were placed at the switching end of an existing pulse-forming network. Each diode was connected anti-parallel with a Super-GTO switch [1, 2]. A general schematic of the test circuit is shown in Figure 5. During the evaluation process, the number of capacitors in the network varied between five and twelve. Inductance between capacitors was fairly low, but the inductor at the anode of the SGTO switch was adjusted a number of times to increase ringing and deliver more current to the diodes. Several diodes were pulsed individually at increasing voltage and current levels until failure in order to narrow down the peak current limitation of the devices.

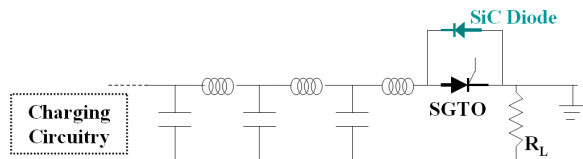


Figure 5. General circuit schematic for diode evaluation.

Different packaging options were also explored. The first group of diodes was encased in hard, caramel-colored, high temperature epoxy which had some elasticity added to it for better CTE matching to the silicon carbide. Because it is preferable to have a removable insulation for post-testing analysis, some diodes were instead insulated with a green, silicone-based epoxy. This epoxy requires a molded container to hold the shape while it sets. The first two packaging designs had the copper anode and cathode tabs extending away from the diodes in opposite directions. Diodes were initially connected in the circuit by clamping on to the tabs with quick-disconnect terminals. After high current pulsing, it looked like the tabs on some of the diodes had pulled out of the clamps as an effect of the magnetic forces. From that point, ring terminals were soldered onto the tabs so that the diodes could be bolted into place in the test bed. These different packaging and connection methods are shown in Figures 6 and 7.

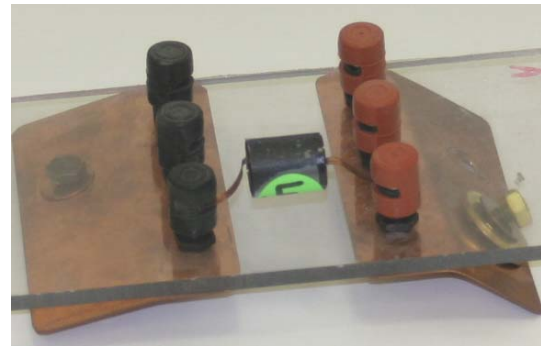


Figure 6. Single diode encased in hard epoxy and clamped into circuit using quick disconnect terminals. Overall dimensions of barrel-shaped epoxy encasing are 2.2 cm length and 1.7 cm diameter.



Figure 7. Diode packaged in similar but hollow hard epoxy barrel which was filled with silicone epoxy. Ring terminals were used to clamp the anode and cathode tabs onto quarter-inch brass bolts.

B. Results

The peak pulse current reached with any single diode was 5.9 kA. This current pulse was repeated for several single shots in order to determine if the diode would switch reliably at this level. After twenty-five pulses, the diode catastrophically failed in blocking mode during

charge-up of the PFN. No silicon carbide material remained, only scattered chips of epoxy. A photo of the test fixture is shown in Figure 8. During the last few pulses prior to failure, a flash of light was spotted inside the package, and it is believed that a disconnect was developing where the copper tab met the gold contact of the diode. This could have been due to the heat generated during each pulse and/or any mechanical flexing of the diode chip. Additional resistance at the damaged contact could add further to the heating and speed up the failure. After this point in testing, diodes were limited to a pulse current of 5 kA, or 100x their rated continuous current.



Figure 8. Clamp fixture which held failed diode. Lexan backing shows carbon debris. Clamp terminals had copper transfer from the anode and cathode tabs.

At a peak current of 5 kA and a base pulse width of 300 μ s, one of the diodes was pulsed over 100 times without failure. This was equivalent to an action of $3.5 \times 10^3 \text{ A}^2$ s per pulse. The diode blocked a PFN charge of 3.2 kV prior to each switching event. Current switched through the diode is shown in Figure 9. Further discussion of device failures will be included in the next section which focuses on pulsing parallel diodes.

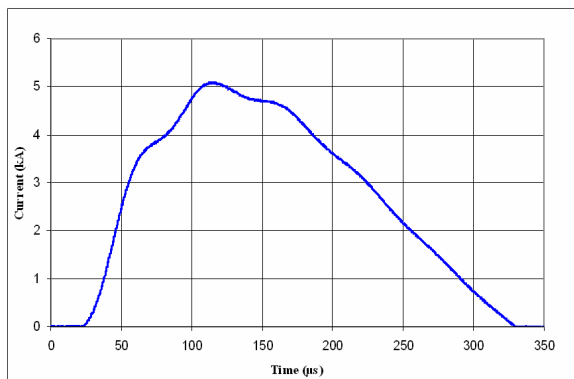


Figure 9. Pulse current of 5 kA switched over 100 times without device failure.

The high current forward voltage drop of the diodes was measured during pulsing using both high voltage differential probes. At a current of 3800 A, the measured voltage was 16 V. To double-check this value, diodes were also pulsed on a high power curve tracer up to the 350 A limit of the instrument. Curves were extrapolated from 350 A up to 3800 A, and an expected voltage drop

of 16-17 V was verified. This is equivalent to an on-state resistance of 3-4 milli-ohms.

III. PARALLEL DEVICES

A. Procedure

With the goal of packaging diodes into compact modules capable of higher peak currents, it was important to determine whether the diodes would be able to share current well when connected in parallel. Previous experience showed that when current is not distributed equally across parallel components, premature device failure becomes much more likely. Current sharing is dependent on both how well matched the devices are and how the current is bussed. [4] Initially, individually packaged diodes were matched based on the level of high voltage they blocked with a permitted leakage of up to 0.1 mA. Five diodes were bolted in parallel to heavy copper strips forming the anode and cathode buss connections (Figure 10). The diode with the shortest anode path had the longest cathode path, etc., so each diode's overall current pathway was equal in length.

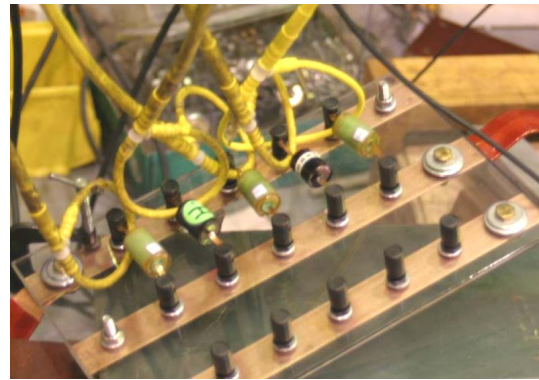


Figure 10. Five diodes connected in parallel to copper busses. Rogowski coils were used to monitor the portion of current carried by each diode.

The set of five diodes was pulsed at increasing levels while current sharing between the diodes was monitored. Parallel diodes were pulsed in the same circuit used for single diodes, but the inductor at the SGTO (see Figure 5) was increased to send more current through the diode pathway while still staying within the blocking voltage limitation of the diodes and the forward current limitation of the SGTO.

A goal of 40 kA was developed, which called for eight parallel diodes, assuming each one would carry about 5 kA. To optimize current sharing while minimizing magnetic forces, the diode packaging and the current buss were modified. Rather than having the anode and cathode copper tabs extend in opposite directions from each device, one lead was bent back so that anode and cathode tabs extended out of the epoxy on the same side (Figure 11). Eight of these diodes were lined up along a thin strip

of G-10 insulation and clamped with heavier copper anode and cathode busses (Figure 12).

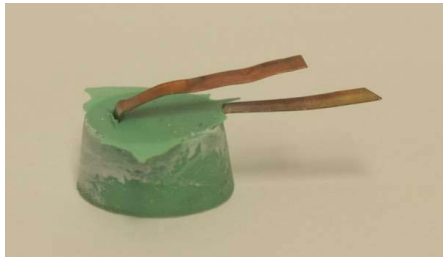


Figure 11. Third package design for SiC diode. Anode and cathode tabs extend in the same direction. The diode is encased in the silicone-based removable epoxy with rough dimensions of 1 cm height and 2 cm diameter.



Figure 12. Clamped buss bars with eight diodes in parallel. Circuit connections were made at the left end.

Before the whole assembly of eight was put together, the curve tracer was used to compare I-V curves for a collection of diodes. Eight diodes that appeared well-matched in forward drop were chosen for parallel pulsing. Overall, the diodes varied by tens to hundreds of millivolts at the 350 A level, as shown in Figure 13.

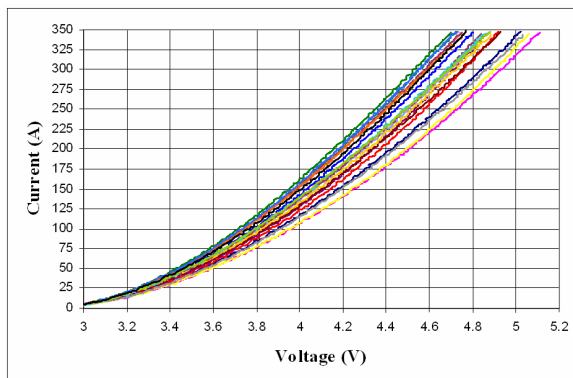


Figure 13. Positive I-V curves for twenty SiC diodes.

B. Results

The peak current switched with five diodes in parallel was 23 kA. As shown in Figure 10, Rogowski coils were attached around each diode to monitor current sharing. The best sharing reached with this test setup had each

diode carrying within $\pm 7\%$ of ideal sharing (with 'ideal' being 4.6 kA per diode). The width of the current was wider than it was for pulse evaluations of single diodes because of adjustments to the capacitance and inductance of the test bed. The current waveforms for the five diodes are shown in Figure 14. With a pulse width of 510 μs at the base, each diode was subjected to an action of about $4.8 \times 10^3 \text{ A}^2\text{s}$.

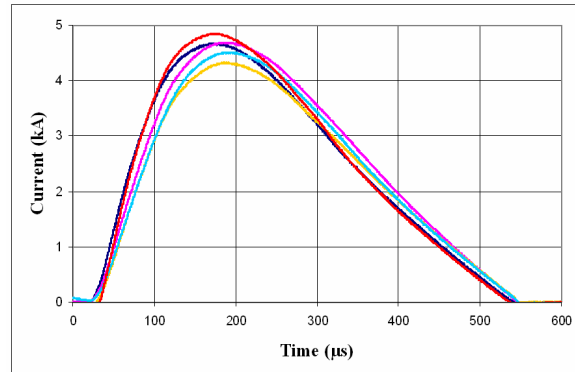


Figure 14. Current carried by each of five diodes switched in parallel. The highest current was 4.8 kA, and the lowest was 4.3 kA.

Parallel switching was done with more than one group of five diodes. Not all groups shared as well as the results shown in Figure 14. This was attributed to both mismatching of the diodes' on-state resistance and uncanceled magnetic fields which affected the diodes' currents depending on where they were physically positioned in the test bed. Once the diode packaging and buss bars were redesigned, it was believed that the diodes would share well consistently.

For eight paralleled diodes, the peak total current switched was 39 kA, which is close to the original goal of 40 kA (Figure 15). Because of the close coupling of the anode and cathode leads and the clamped buss bars, it was not possible to fit Rogowski coils into the setup to measure individual currents; only the total current at the buss was monitored. For future testing, the plan is to attach longer copper tabs to the diodes so that each anode or cathode may be bent slightly to accommodate a 4.5 mm diameter coil. It is assumed that the eight diodes that were tested shared current fairly well because 5 kA (approximately 1/8 of the total current) had been settled on as a safe peak current during the aforementioned evaluation of individual devices. If any of these diodes were carrying much more than 5 kA, it is likely that it would have failed short, if not catastrophically.

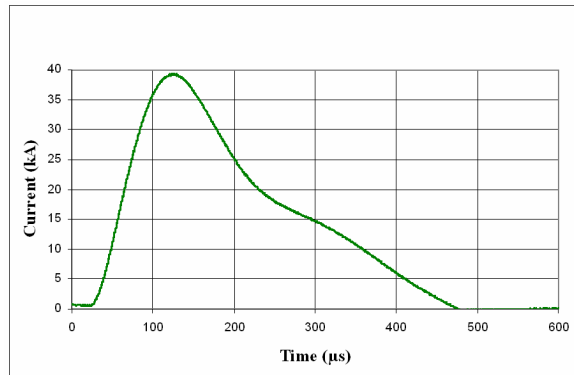


Figure 15. Peak current pulsed with eight parallel diodes. The circuit components had been changed again, affecting the shape of the pulse.

During this full study of high power diode pulsing, quite a few diodes did fail catastrophically while in reverse blocking mode. Initial concerns were to double-check that the epoxy insulation was holding up and to make sure not to high-pot devices past their rated 6 kV. When devices were high-potted on the bench or characterized on the curve tracer in between pulses, it was found that after a number of high current pulses, the diodes were starting to lose their high voltage blocking capability. Many diodes that blocked greater than 6 kV prior to pulsing ended up leaking a milliamp when only 200-300 volts were applied. Similar degradation in blocking capability was seen with SiC thyristors. [5] Along with the increased reverse leakage, there was a very slight increase in forward drop. One possible cause for these changes is the formation of stacking faults within the silicon carbide. If more stacking faults develop with each high current pulse, the device may also be dissipating more heat every time. It is possible that limiting the devices to a lower pulse current, like 3 or 4 kA, may cut down on the number of devices that fail. A study will likely be performed to better understand the relationship between peak current, number of pulses and failure mode.

IV. SUMMARY

Silicon carbide 50 A diodes have been evaluated under high pulse current stresses to determine how they may fit into future Army pulsed power systems. A peak current of 5 kA was determined to be a reliable switching current at pulse widths lasting a few hundred microseconds. Paralleled diodes in groups of five and eight were also switched up to a total current of 39 kA. Future work with these devices will involve packaging and evaluating them in compact modules, as well as further studying the differences between a diode that survives many pulses versus one that fails. Larger area SiC diode chips are also in development so that an optimum device size may be determined.

V. REFERENCES

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