SILICON DIODE EVALUATED AS RECTIFIER FOR WIDE-PULSE SWITCHING APPLICATIONS

Heather O'Brien, Aderinto Ogunniyi, Charles J. Scozzie
U.S. Army Research Laboratory, 2800 Powder Mill Road
Adelphi, MD 20783 USA
William Shaheen
Berkeley Research Associates, 6551 Mid Cities Ave
Beltsville, MD 20705 USA
Victor Temple
Silicon Power Corp., 958 Main St., Suite A
Clifton Park, NY 12065 USA

Abstract

Silicon diode chips ("S-diodes") designed by Silicon Power Corporation were explored as a more power-dense, lighter-weight replacement for traditional hockey-puk diodes in pulse switching applications. The 3.5 cm^2 S-diode has the same area as Silicon Power's Super-GTO chip with reverse blocking capability above 6 kV. The diodes evaluated in this study were individually packaged at Silicon Power, then statically characterized and pulsed at the Army Research Laboratory. In series with the SGTO, the diode was pulsed with a half-sine shaped current of 5.5 kA with a pulse width of 1 ms. The action was calculated to be 1.6 x 10^4 A^2s with a peak power of about 55 kW. The diode was also utilized in a crowbar configuration, clamping negative current ringing from the circuit's inductance. In this function, the diode blocked 4.5 kV DC and then conducted 2.0 kA. Several diodes were individually pulsed in the circuit for 1000 shots at this level without increasing forward drop or reverse leakage, demonstrating feasibility for use in high-voltage, wide-pulse power systems.

I. INTRODUCTION

Army switching needs call for compact, high-power symmetric-blocking pulse switches. While larger, wafer-scale silicon thyristors are capable of symmetric voltage hold-off, they are too bulky to meet the volume and weight requirements of vehicle-mounted systems. The Army Research Laboratory (ARL) has demonstrated very promising switching performance with Silicon Power's Super-GTO, but the device cannot block high voltage applied in the reverse direction [1, 2]. Connected in series with the SGTO, a diode can protect the switch if it can handle the same level of pulse current and then quickly transition to block a subsequent negative voltage swing.

In the lab, 50 mm-diameter diodes have been used in the evaluation circuits to protect the switching components under test. In order to take full advantage of compact pulse switches for a vehicle, though, it is desirable to pair them with power-dense diode packages. It will be shown in this paper that, based on current density in the silicon, the 3.5 cm^2 S-diode has a 1-ms pulse current density rating similar to that of larger, commercially-available silicon diodes. The advantage of the S-diode lies in the packaging design, which limits overall volume and weight. Each diode chip can be solder-mounted and does not require any high-pressure clamping. Diodes can be integrated into higher-current, multi-chip diode modules, or combined in packages with Super-GTO switches.

The information presented here on the S-diode's wide-pulse performance is preliminary. More complete testing was scheduled but had to be postponed in order to install safety upgrades at the lab. The diode's pulse current is expected to exceed that of the Super-GTO switch by at least 15%.

II. DESIGN AND PACKAGING

The S-diode was designed by Silicon Power. It is fabricated as a size-12 chip with a footprint of 3.5 cm^2 and an edge termination about 2 mm wide. For high voltage blocking, the termination doping is 2.0 x 10^{12} per cm^2. At this time, these diodes are not being marketed commercially. Prior to ARL's application-based evaluations, they were tested by Silicon Power at narrower pulse widths and faster rise times.

The diodes utilized in this study were individually packaged at Silicon Power. Lead-tin solder attaches the backside of each device to a copper-moly-copper base plate, serving as a cathode connection. Copper tabs provide connections to the anode surface of the diode. A non-conducting plastic shell is epoxied to the base plate, and the remaining open well around the device is then filled with insulating epoxy (Fig. 1).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2009	**N/A**	-

4. TITLE AND SUBTITLE
Silicon Diode Evaluated As Rectifier Forwide-Pulse Switching Applications

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory, 2800 Powder Mill Road Adelphi, MD 20783 USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
Silicon diode chips (S-diodes) designed by Silicon Power Corporation were explored as a more power-dense, lighter-weight replacement for traditional hockey-puk diodes in pulse switching applications. The 3.5 cm2 Sdiode has the same area as Silicon Powers Super-GTO chip with reverse blocking capability above 6 kV. The diodes evaluated in this study were individually packaged at Silicon Power, then statically characterized and pulsed at the Army Research Laboratory. In series with the SGTO, the diode was pulsed with a half-sine shaped current of 5.5 kA with a pulse width of 1 ms. The action was calculated to be 1.6 x 104 A2s with a peak power of about 55 kW. The diode was also utilized in a crowbar configuration, clamping negative current ringing from the circuits inductance. In this function, the diode blocked 4.5 kV DC and then conducted 2.0 kA. Several diodes were individually pulsed in the circuit for 1000 shots at this level without increasing forward drop or reverse leakage, demonstrating feasibility for use in high-voltage, wide-pulse power systems.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

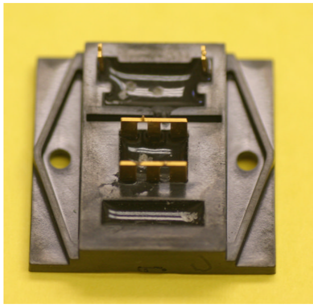

Figure 1. Packaged S-diode: 3.5 cm x 3.6 cm x 0.8 cm. Anode tabs protrude from the center of the package. A cathode connection can be made to the other pair of tabs at the top of the package or to the base plate.

The packaging used for the individual S-diodes measures 10 mL and weighs 22 g. A module of eight parallel diodes, planned for future testing, would measure 96 mL and weigh 250 g based on current Super-GTO module assemblies.

In the pulse circuit, the anode connection was made by clamping copper plates to the small tabs extending from the top of the package. The cathode connection was made through the base plate of the package which was held to the back of a Super-GTO (for the series diode) or to a copper bus bar (for the anti-parallel diode) with 4-40 screws (Fig. 2).

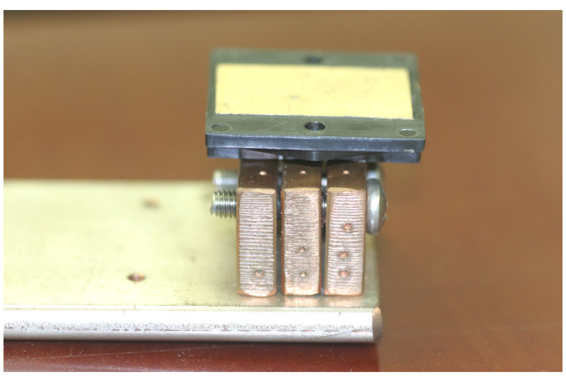

Figure 2. Connection of S-diode package for pulse testing. Anode tabs were clamped between copper plates, and the Super-GTO switch was added back-to-back with the diode.

Prior to pulsing, the diodes were high-pot tested on the bench top for reverse voltage blocking at 100 µA leakage, or 50 µA/cm^2 over the 2.0 cm^2 active area. Of the twenty diodes received, sixteen of them blocked 6.1-6.3 kV DC. The other four blocked between 3-4 kV. The diodes typically blocked 1 kV less than the present generation of Super-GTO chips from Silicon Power, due to different doping at the edge termination [3].

III. EVALUATION METHODS

A. Pulse Evaluations

The S-diode was evaluated both in series and in anti-parallel with a silicon Super-GTO switch. The main pulse circuit consisted of a high-energy capacitor bank, an inductor constructed at ARL, a Super-GTO from Silicon Power Corp., and a high-wattage resistive load (Fig. 3). In the series configuration, the diode started off forward-conducting high pulse current along with the Super-GTO, then was required to go into reverse voltage blocking at the end of the current pulse. The forward pulse was 1 ms in duration, and the reverse blocking time lasted 1.1 ms. The anti-parallel diode was in reverse blocking mode for several seconds during charging of the capacitors and the main current pulse, then switched into forward conduction for 1.1 ms as the inductor current rang negative. A low-resistance power resistor was connected in series with the anti-parallel diode in order to limit the current. Without this anti-parallel diode, the series diode would be forced into a hard reverse recovery when the voltage at the inductor rang negative. The diode would already be at an elevated temperature due to the preceding forward current pulse. Forcing a rapid recovery at this time failed a few series diodes before the anti-parallel diode was added to the system.

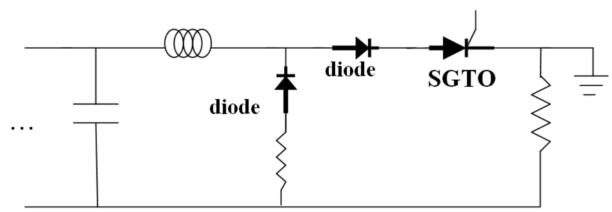

Figure 3. Schematic of the circuit used to evaluate both Super-GTOs and S-diodes.

The series-connected diode also played a role during evaluations of recovery time and dV/dt immunity for the Super-GTO. To determine the switch's forward recovery time, high voltage was applied to the GTO's anode at an adjustable time delay following the main forward current pulse. In order to control the rate at which the high voltage was applied and to ensure that the Super-GTO was semi-isolated for this test, the series diode was utilized in blocking mode. In this way, the main capacitor bank and inductor were not being recharged, and any current drawn would suggest leakage through the Super-GTO or the diode. Similarly, high voltage applied for the dV/dt tests would only appear at the GTO's anode, and high dV/dt could be generated with a small, narrow pulse current on the order of 15 A.

B. Results

Along with the Super-GTO, the series diode conducted 5.5 kA of pulse current (at 2.8 kA/cm^2 over the active area). The switch and diode pairs were pulsed over 1000 times each at a very low duty cycle and did not subsequently show any degradation in DC voltage blocking capability. Eight diodes were successfully evaluated in this configuration. Because their active area is entirely emitter, the diodes are expected to have greater pulse current capability than the Super-GTOs, but they have not been evaluated up to their limit at this time.

The forward voltage drop of the series diode was monitored at various pulse current levels and plotted on an I-V curve (Fig. 4). At the 5.5 kA peak pulse current, the voltage drop was 10 V, corresponding to a power dissipation of 55 kW (Fig. 5). These are about the same voltage drop and power dissipation as for the Super-GTO.

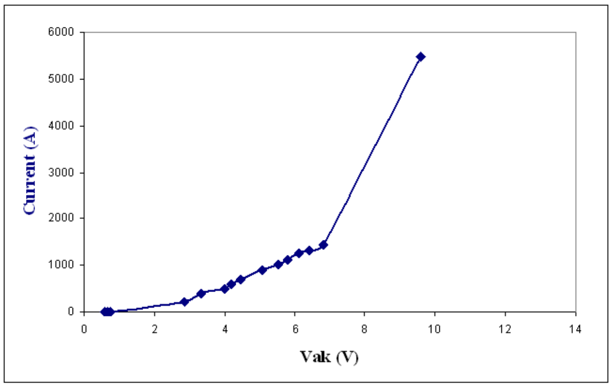

Figure 4. Preliminary I-V curve for S-diode at high-current pulse.

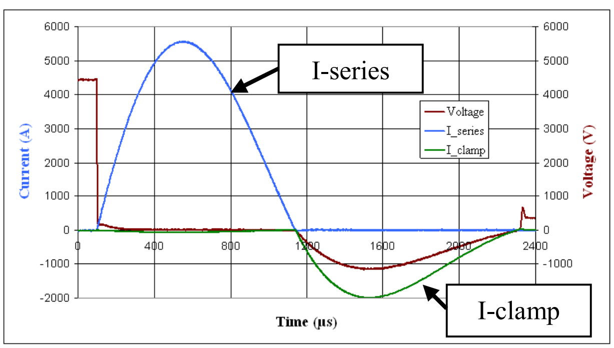

Figure 5. Complete voltage and current waveforms for series and anti-parallel diodes. Voltage measurement shown is across both the series diode and the Super-GTO.

The S-diode proved to be a good match for use with the Super-GTO because of the design similarities between the devices. At the time when the main current pulse falls to zero, a very smooth transition is seen where the series diode enters blocking mode and the anti-parallel diode starts to conduct (Fig. 6). No delay is apparent. With the impedances presently in use in this pulse circuit, the series diode was required to block -1.2 kV following the forward current pulse. The anti-parallel diode blocked 4.5 kV during the charging of the capacitor bank and conducted 2.0 kA when the system's current rang negative. Further testing needs to be done to confirm full current capability (>5.5 kA) for the anti-parallel diode.

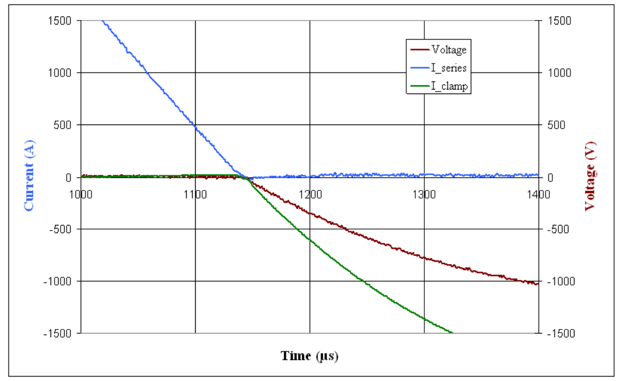

Figure 6. Enlarged view of transition point where series diode enters blocking mode and anti-parallel diode begins to conduct.

The S-diode continued to work well in blocking mode during the Tq and dV/dt tests. In the Tq evaluation, the series diode has already transitioned into blocking mode, and the application of high voltage at the Super-GTO merely increases the magnitude of voltage across the diode from –1.2 kV to –5.4 kV (Fig. 7). The S-diode was able to block this voltage following forward conduction without any notable reverse leakage. Diodes were high-potted under DC conditions after switching and continued to block >6 kV.

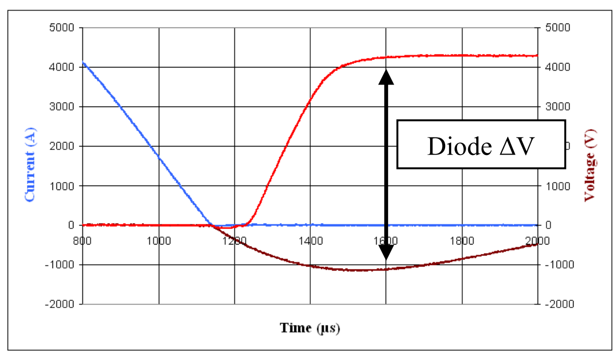

Figure 7. Voltage waveform for typical 4.5 kV Tq recovery test of Super-GTO. The series diode blocked -5.4 kV.

The S-diode was demonstrated at a 1-ms pulse current density of 2.8 kA/cm^2 over the active area, or 1.6 kA/cm^2 over the footprint area of the chip. These values are likely to increase some once higher current testing is completed. This current capability is similar to what is listed in the datasheets for present commercially-available diodes from ABB, VRE, and Silicon Power. ABB's 60 mm freewheeling diode 10H6004 has a rated 1-ms pulse current of 44 kA, or about 1.6 kA/cm^2 over the area of the silicon [4]. VRE's 5000-series hockey-puk diodes are rated for about 60 kA, or 3.0 kA/cm^2 [5]. Silicon Power also has a commercially available 53-mm press-pak rectifier diode, the A780, rated at about 40 kA, or 1.8 kA/cm^2 at this pulse width [6]. Therefore, the S-diode does not carry much advantage in the category of current density. What it does provide is a close match for the Super-GTO devices and, more importantly, a thin, light-weight package whose buss requirements are simple and do not require kN of clamping force.

C. Further Testing

More data was intended to be included in this paper, such as maximum pulse current capability and more complete I-V curves for the S-diodes. The Super-GTO and diode evaluations were put on hold for several weeks in order to add safety upgrades to the high power test beds at the lab. Further evaluations are planned for the diodes, both individually and in 8-chip modules, similar to the standard-unit Super-GTO modules that ARL utilized in previous narrower-pulse switching [2]. The diode modules would be combined in series with Super-GTO modules in order to create symmetric 6 kV switching units capable of an estimated 40 kA at the 1-ms pulse width.

IV. SUMMARY

S-diodes designed by Silicon Power Corp. were used with Super-GTOs to create symmetric high-power switches for wide-pulse Army applications. The diodes proved to be a good match for the Super-GTOs. They switched up to 5.5 kA of 1-ms wide pulse current and reverse-blocked up to 4.5 kV in the evaluation circuit. The diodes showed greater than 6.0 kV DC blocking on the bench top. The diodes exhibited a smooth transition between conduction and blocking in this type of application. The data collected on these devices so far supports the plan to assemble the S-diodes into larger modules for higher current switching and rectification.

V. REFERENCES

[1] K. Brandmier, "Solidtron™ CCSTA14N40 N-Type, ThinPak™ Preliminary Data Sheet," Silicon Power Corp., Malvern, PA, 2005.

[2] H. O'Brien, W. Shaheen, R.L. Thomas, Jr., T. Crowley, S.B. Bayne, and C. J. Scozzie, "Evaluation of Advanced Si and SiC Switching Components for Army Pulsed Power Applications," *IEEE Trans. Magn.*, vol. 43, no. 1, pp. 259-264, Jan. 2007.

[3] A. Ogunniyi, H. O'Brien, W. Shaheen, C.J. Scozzie, and V. Temple, "Device Optimization and Performance of a 3.5 cm2 Silicon SGTO for Army Applications," Proc. of the 17th IEEE PPC, 30 June – 2 July 2009, Washington, D.C.

[4] "Fast Recovery Diodes," High Power Semiconductors Short Form Catalogue, 2008 Edition, pp. 11-12, ABB Switzerland Ltd., Lenzburg, CH.

[5] "Half-Sine Diode Peak," datasheet, updated 22 Nov. 2006. Available from VR Electronics Co. Ltd., Ontario, CA.

[6] "A740, A750, A780 53 mm Rectifier Diodes," Silicon Power, Malvern, PA, [Online], 2001 [cited June 2009], Available: http://www.siliconpower.com Directory: Large/Comp_data File: a780.pdf