Characterization and Modeling of Silicon-Carbide Power Devices*

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I. Introduction

New power semiconductor devices have begun to emerge that utilize the advantages of silicon carbide (SiC) As SiC power device types are introduced, circuit performance and reliability characterization is required for system designers to adopt the new technology. Furthermore, the development of circuit simulator models is required to enable the devices to be fully utilized in the circuit and system design process. The purpose of this paper is to demonstrate device metrology and modeling methodologies required to facilitate market penetration of SiC power devices.

Although new device designs are routinely characterized for DC conduction and switching, additional tests are required to evaluate the performance for circuit application conditions. Additionally, characterization is required for Forward-, and Reverse-Bias Safe Operating Area, FBSOA and RBSOA. The higher intrinsic temperature and thermal conductivity of SiC provide potential robustness advantages although the actual FBSOA and RBSOA capabilities are highly dependent on device type, design, and material parameters. Finally, device performance evaluation should include interaction between system components, total system energy efficiency, and other system performance considerations such as reliability and ElectroMagnetic Compatibility (EMC).

Almost all circuit simulators contain library parts for various commercially available silicon (Si) devices. The library of component models enables the circuit designer to directly evaluate the influence of different components on the overall system performance and enables optimization of circuit parameters to fully utilize the components. The development of SiC component model libraries requires compact physics based models, parameter extraction procedures, and validation procedures to demonstrate model performance for the full range of application conditions. SiC power device models and extraction procedures can be adapted from those of the Si device counterparts. However, the physical and structural parameter values vary substantially from those typically used to model Si devices requiring substantial modification of the model equations and parameter extraction procedures.

II. Conductivity and Switching Performance

SiC power devices are expected to show superior conductivity and switching performance compared to devices made with other semiconductor materials. This is primarily due to the order of magnitude higher breakdown electric field of SiC compared to Si. The higher breakdown electric field allows the design of SiC power devices with voltage blocking

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* Contribution of the National Institute of Standards and Technology is not subject to copyright. This work was partially supported by the DARPA Megawatt Solid-State Elec. Program and an NSF GOALI Award, and made use of ERC Shared Facilities supported by the National Science Foundation award EEC-9731677.

layers that are an order of magnitude thinner and an order of magnitude more highly doped than those of Si devices. For majority carrier power devices, this can yield a SiC power device with two orders of magnitude higher conductivity. For minority carrier devices, the thinner voltage blocking layer results in a smaller diffusion length L required for conductivity modulation and thus can result in a two-order-of-magnitude faster switching speed due to the reduced lifetime τ according to: $L = \sqrt{D\tau}$. In the case of power diodes, it has been shown that a 1500 V SiC Merged PiN Schottky diode (majority carrier device) provides superior performance over Si diodes with voltage ratings of 600 V to 1500 V [1], and that a SiC PiN diode (minority carrier device) has superior performance compared to Si diodes with voltage ratings from 2000 V to 5000 V (Table 1) [2].

Full SiC diode characterization requires extending the temperature range well beyond the 125 °C used for Si power devices and requires switching measurments for higher speeds and lower capacitances than normally used for Si power devices. A new SiC power diode test system was developed that enables testing SiC power diodes for the full range of application circuit conditions by varying the switching current, voltage, di/dt, dv/dt, and temperature [1]. Varying dv/dt makes it possible to identify the portion of the diode recovery due to charge storage and the portion due to device capacitance. For example, Fig. 1 shows the current and voltage waveforms of the 0.25-A, 5000-V SiC PiN diode for three different dv/dt values obtained using different driver capacitor values. For the case where no driver capacitance was added (C=0 pF), the reverse current waveform consists of a stored charge recovery portion followed by the capacitive portion. For the case of the highest driver capacitor value (2000 pF), dv/dt is substantially reduced and the current required to charge the internal diode capacitance is minimal. Thus, the waveform consists of a stored charge recovery portion followed by a small current tail due to decay of the remaining stored charge.

III. Safe Operating Area Performance

Power semiconductor devices are frequently employed in hard-switching applications, where the device is required to turn off high currents under inductive loading conditions. Ruggedness of devices used in such applications is a desirable feature and is characterized by RBSOA measurements. Historically, bipolar transistors had severe limitations on their RBSOA. RBSOA failure occurs because dynamic switching conditions result in current constriction leading to excessive current density in a small region of the device leading to destruction [3]. It was originally thought that power MOSFETs would be immune from the RBSOA restrictions of the bipolar transistors. However, due to the internal parasitic bipolar of the power MOSFET structure, some RBSOA limitations persisted with the earlier power MOSFET devices. Further development of the power MOSFET eliminated these restrictions and resulted in the unclamped inductive switching (UIS) energy-rated devices that withstand avalanche conditions and uniformly heat the chip surface (no current constriction).

Figure 2 shows an RBSOA measurement of a SiC power MOSFET obtained using the non-destructive RBSOA tester developed at NIST [4]. The high-speed shunt protection circuit of the NIST tester detects the voltage collapse at the onset of RBSOA failure and rapidly diverts the inductor current away from the device thus preventing destruction of the device. This enables repeated failure tests to be performed on a single device. A 600-V SiC MOSFET was tested for a variety of conditions up to: 1-A drain current, 1-A turn off gate drive current, and 500-V clamp voltage. The measurements indicate that the device is more rugged than Si power bipolar transistors. Further RBSOA improvement is expected for the SiC power MOSFET. It remains to be determined if the RBSOA performance of SiC MOSFET and bipolar switching devices will exceed that of Si MOSFETs.

IV. Application Circuit Performance

The selection of a semiconductor device depends upon many factors including overall system energy efficiency, voltage and current stress on other components, and the requirements for auxiliary components such as drive circuits, cooling systems, and protection systems. The influence of a component on the overall system energy loss is often through reducing the losses induced in other components. For example, Fig. 3 shows the reduction of MOSFET turn-on losses that results from replacing a silicon diode with a SiC Junction Barrier Schottky (JBS) diode. This also reduces the loss and cooling requirements for the diode, reduces the current stress on the MOSFET, and reduces EMI Emissions [1].

In general, the circuit design and component selection are done together. Figure 4 shows an auxiliary resonant chopper soft switching circuit. In this circuit, it is essential for the auxiliary diode D_r to have low reverse recovery current because the reverse recovery results in an excessive voltage spike. The voltage spike requires the addition of protection such as a saturable reactor or snubber. These protection elements contribute additional energy loss to the system. By using the SiC JBS diode for D_r, the protection devices can be eliminated resulting in a system with increased efficiency and lower component count [5].

V. Circuit Simulator Model Development

The development of dynamic electrothermal circuit simulator models for SiC power devices requires physics based model equations, robust circuit simulator implementation, and a systematic parameter extraction procedure. Because extensive effort has been dedicated to the development of Si power device models, the SiC models are adapted from Si models. In this work, a SiC power diode model was developed based upon the Mantooth model for Si power diodes that is provided within the Saber simulator [6]. The models accurately describe the temperature dependence of on-state characteristics (e.g. Fig. 5) and reverse-recovery switching waveforms (e.g. Fig. 6) for a wide range of circuit conditions. A parameter extraction sequence has also been developed (subject of future publication) and parameters have been extracted for SiC MPS and PiN diodes with current ratings from 0.5 A to 20 A, and voltage ratings from 600 V to 10 kV.

VI. Conclusion

Acceptance and effective utilization of SiC power devices requires: 1) demonstration of superior conduction and switching performance, 2) evaluation of performance in power converter applications, 3) demonstration of safe and reliable operation, and 4) development of compact circuit simulation models to aid in the design of systems utilizing the devices.

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	Blocking Voltage	Forward Voltage Drop	Reverse Recovery Time
SiC PiN	5000	5.7	6
VMI X50FF3	5000	12.5	30
VMI X20FF3	2000	7.5	30
VMI 1N6523	3000	5.0	70
VMI 1N6524	4000	7.0	70
Philips BYX105G	5000	10.9	600
Philips BYX106G	5000	12.7	350
Philips BYX107G	5000	15.8	175
Philips BYX108G	5000	27.7	50

Table 1. Comparison of 5000-V SiC diode and Si diodes.

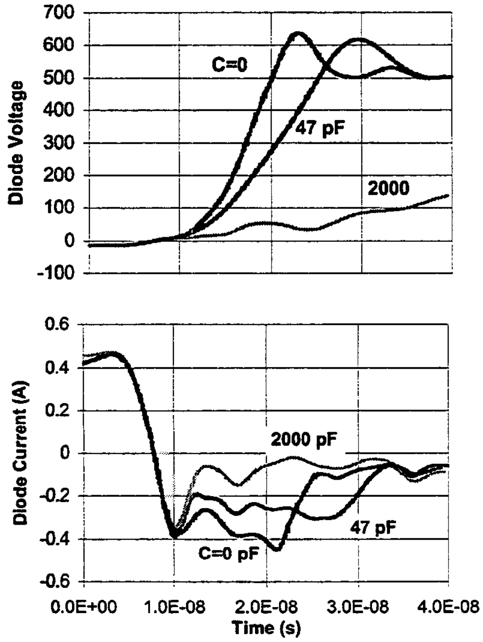

Fig. 1. Reverse recovery current and voltage waveforms for the 5000-V SiC PiN diode

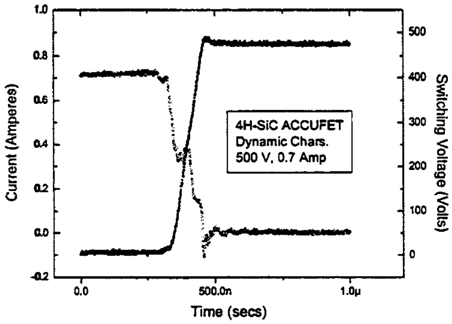

Fig. 2. RBSOA measurments of SiC MOSFETs.

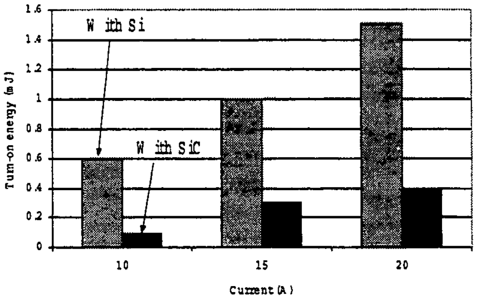

Fig. 3. Turn-on energy of MOSFET with SiC JBS diode and ultra fast Si diode under different load currents.

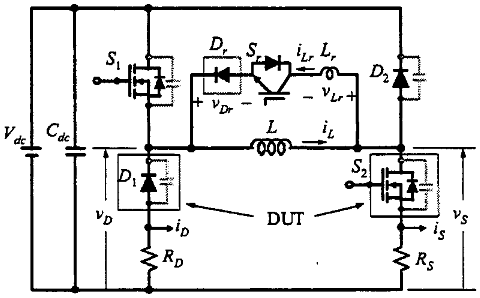

Fig. 4. The auxiliary resonant chopper test circuit.

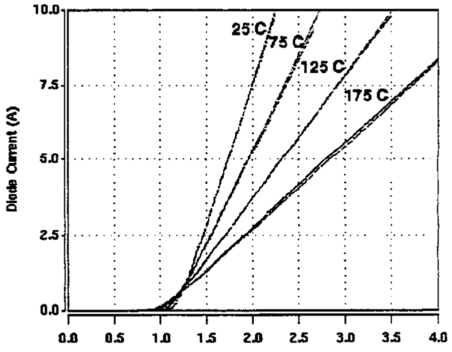

Fig. 5. Simulated (dashed) and measured (solid) on-state characteristics for the 1500 V, 10 A SiC MPS diode

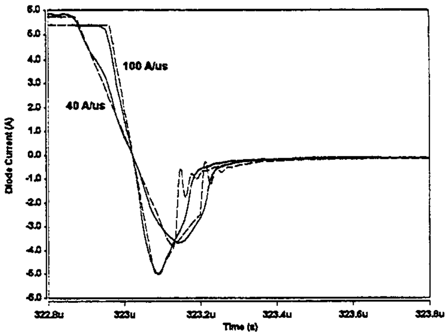

Fig. 5. Simulated (dashed) and measured (solid) reverse recovery waveforms for a 5 kV, 20 A SiC PiN diode