10 kV, 120 A SiC Half H-Bridge Power MOSFET Modules Suitable for High Frequency, Medium Voltage Applications

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Abstract— **The majority carrier domain of power semiconductor devices has been extended to 10 kV with the advent of SiC MOSFETs and Schottky diodes. The devices exhibit excellent static and dynamic properties with encouraging preliminary reliability. Twenty-four MOSFETs and twelve Schottky diodes have been assembled in a 10 kV half H-bridge power module to increase the current handling capability to 120 A per switch without compromising the die-level characteristics. For the first time, a custom designed system (13.8 kV to 465/√3 V solid state power substation) has been successfully demonstrated with these state of the art SiC modules up to 855 kVA operation and 97% efficiency. Soft-switching at 20 kHz, the SiC enabled SSPS represents a 70% reduction in weight and 50% reduction in size when compared to a 60 Hz conventional, analog transformer.**

I. INTRODUCTION

Silicon carbide has carried the promise of revolutionizing high power, high frequency electronics for many years. The 4H-SiC polytype with its superior electrical properties has already ushered in a new era of commercially available 600 V, 1200 V, and 1700 V Schottky diodes that have made a dramatic impact in switch-mode power supplies, AC motor drives, and solar inverters. SiC switches like Metal Oxide Semiconductor Field Effect Transistors (MOSFETs), Bipolar Junction Transistors (BJTs) and Junction Field Effect Transistors (JFETs) are approaching commercial release and will enable all-SiC solutions for ultra-high efficiency systems. In this submission, we demonstrate the potential of SiC to create new solid state solutions where silicon simply does not exist—the world's first 10 kV half H-bridge power MOSFET module capable of conducting 120 A per switch and enabling a compact 13.8 kV to 465/√3 V single phase solid state power substation (SSPS) rated at 1 MVA.

II. SIC 10 KV MOSFET AND SCHOTTKY DIODE

A. Device Design

The critical components in the 10 kV modules are the 10 kV, 10 A MOSFET and the 10 kV, 10 A Schottky diode. Both devices are fabricated on 120 µm thick epitaxial layers, doped 6x10^{14} cm^{-3} and grown on 100 mm 4H-SiC substrates (Fig. 1) with micropipe density <1 cm^{-2}. The MOSFET is based on a doubly implanted, cellular structure with nitrided gate oxide and degenerately doped poly-Si gates [1]. The 8.1 mm x 8.1 mm MOSFET chip is the largest MOS switch reported in SiC with individual wafer yields as high as 55%. The diode is a junction barrier Schottky (JBS) containing a non-injecting p+ grid in the active area to attenuate surface fields during reverse blocking while forward

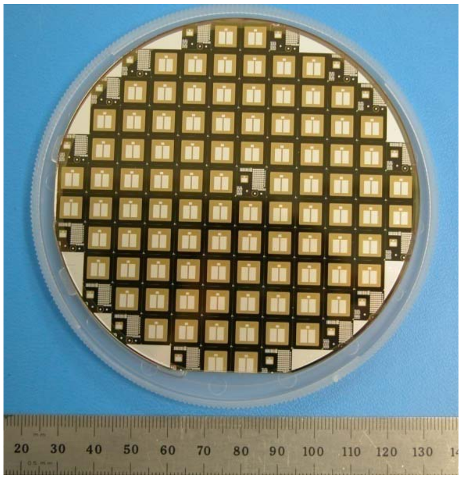

Figure 1. Fully fabricated 10 kV, 10 A MOSFETs (8.1 mm x 8.1 mm die) on a 100 mm SiC wafer.

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conduction occurs through the Schottky contact with majority carriers only [2]. Despite the large 8.3 mm x 10.6 mm chip size, the 10 kV JBS diodes have been successfully fabricated with individual wafer yields as high as 65%.

B. Device Performance

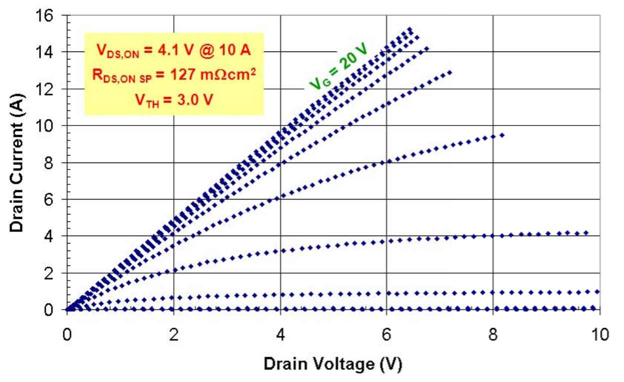

Figure 2. SiC 10 kV, 10 A MOSFET drain conductance showing ~400 mΩ on-resistance with V_G = 20 V.

The static and dynamic characteristics of these 10 kV devices are unprecedented. At room temperature, the MOSFET turns on with a 3 V threshold and conducts 10 A at $V_{DS,ON}$ = 4.1 V when driven with 20 V on the gate (Fig. 2). This corresponds to a specific on-resistance of 127 mΩcm^2 which is dominated by the drift layer resistance. At room temperature, the JBS diode has a 1.2 V knee before conducting 10 A with a V_F = 4 V. Due to their unipolar mode of conduction, both devices exhibit a positive temperature coefficient for on-resistance thereby facilitating their use in a parallel configuration for higher current. In the off state, both devices demonstrate sub micro-Ampere leakage currents at 10 kV while avalanching at 12 kV. Clamped inductive switching measurements reveal fast transition times for the MOSFET and no stored minority carrier charge in the JBS diode reverse recovery. The 10 kV MOSFET turn-on transition (Fig. 3) completes in 150 nsec and requires 351 nC of gate charge. The turn-on waveform is dominated by the capacitive recovery of the large area JBS diode. Thermal modeling studies of the MOSFET and JBS diode show an optimum sizing ratio of 2:1 indicating that the 10 A MOSFET is best matched with a 5 A JBS diode. Even with the oversized JBS diode, the turn-on energy loss is only 4.48 mJ. The turn-off transition (Fig. 4) is similarly fast with the switch commutating to the off-state in 144 nsec without any tailing effects and a miniscule turn-off energy loss of 0.81 mJ. The total power losses are compiled in Table 1 and compared to the closest Si device (two 6.5 kV IGBTs in series). While the Si IGBT switching losses become prohibitively large at frequencies >500 Hz, the superior properties of the SiC devices permit 20 kHz operation with manageable power losses of 160 W/cm^2 and 100 W/cm^2 for the switching and conduction losses, respectively.

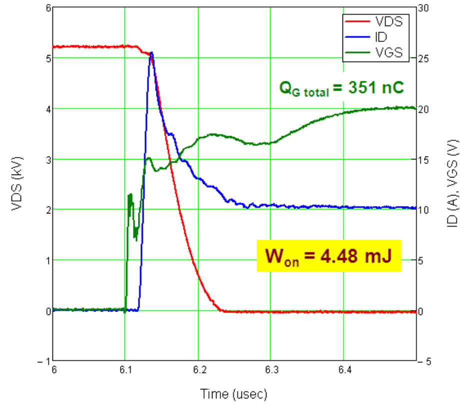

Figure 3. Turn-on waveform for the 10 kV, 10 A SiC MOSFET showing a fast 150 nsec transition with low energy loss despite the large overshoot due to the oversized Schottky diode.

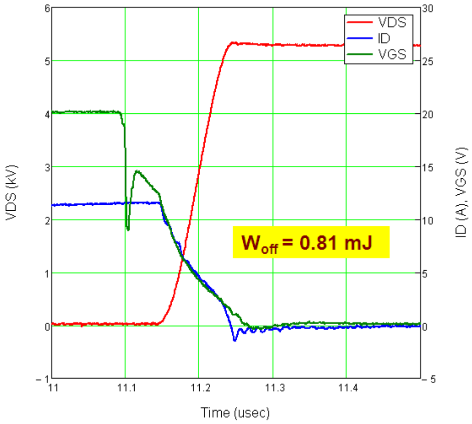

Figure 4. Fast, ultra-low loss turn-off characteristics of the 10 kV, 10 A SiC MOSFET as expected for a majority carrier switching device.

TABLE I. LOSS COMPARISON BETWEEN 10 KV SIC AND SI SWITCH TECHNOLOGIES

Device	**Brkdwn Voltage**	**$P_{switching}$ 500 Hz**	**$P_{switching}$ 5 kHz**	**$P_{switching}$ 20 kHz**	**$P_{conduction}$ 100°C**
Cree SiC MOSFET	12 kV	4 W/cm^2	40 W/cm^2	160 W/cm^2	100 W/cm^2
ABB Si IGBT	2x6.5 kV	72.5 W/cm^2	725 W/cm^2	2900 W/cm^2	182 W/cm^2

C. Device Reliability

In addition to performance, the 10 kV devices are also shown to be very robust. At 150°C for 1000 hrs, both devices demonstrate excellent 10 kV blocking and forward conduction stability. Historical concerns with the SiC gate oxide reliability have been mitigated via nitridation anneal and careful process/design. Time-dependent-dielectric-breakdown (TDDB) measurements performed on small area SiC MOSFETs (identical cellular structure as the 10 kV, 10

A SiC MOSFET with ~10,000x fewer cells) predict SiC gate oxide lifetime to be sufficiently long at operating conditions and comparable to, if not better than, Si MOSFET TDDB at 175°C (Fig. 5). Clamped inductive switching measurements show the SiC devices to be capable of very high dV/dt commutation (Fig. 6) and a square reverse bias safe operating area (RBSOA) bounded by the rated 10 A and 10 kV.

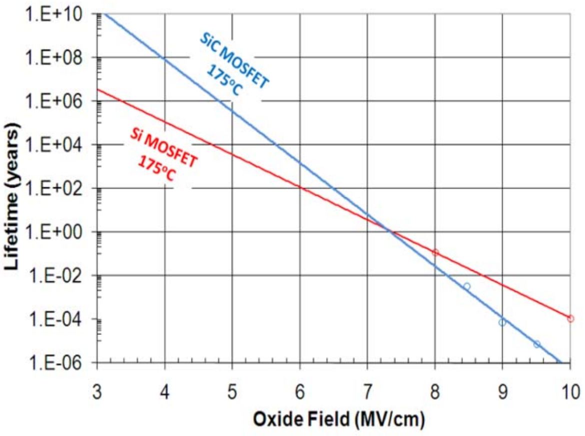

Figure 5. SiC MOSFET TDDB predicts sufficiently long gate lifetimes at 175°C that is comparable to, if not better than, Si MOSFET TDDB results.

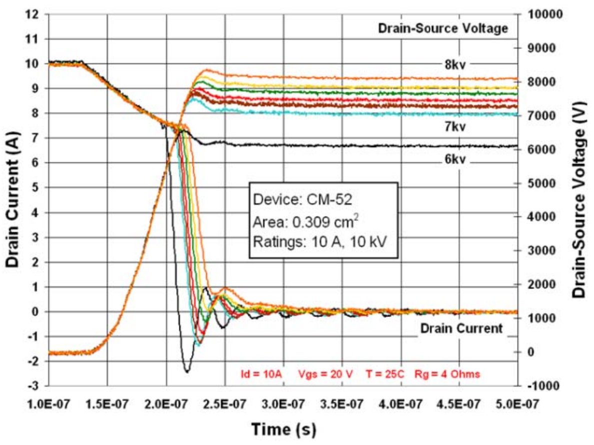

Figure 6. High dV/dt switching tests show stable SiC MOSFET operation out to ~100 kV/µs.

III. 10 kV Half H-Bridge Modules

Working in collaboration with the chip and system designers, the module designers have produced a package platform (Fig. 7) that successfully parallels many devices into two switches in a half H-bridge circuit while maintaining the excellent characteristics demonstrated at the chip level. The 10 kV half H-bridge module is based on a commercial 140 x 190 mm^2 Si IGBT module footprint with low inductance bus-work and appropriate creep/strike distances and encapsulation to permit 10 kV operation. Proper cooling is achieved via commercial off-the-shelf liquid-cooled chill plates. The half H-bridge configuration has an upper and lower switch, each capable of 120 A operation in the on-state. To achieve such high current levels, the 10 kV modules are populated with 12 SiC MOSFETs and 6 SiC JBS diodes per switch in accordance with the aforementioned optimum 2:1 sizing ratio. In order to suppress the device degradation due to the turn-on of the body diode [3], low voltage Si Schottky diodes are placed in series with the SiC MOSFET to prevent reverse conduction. The semiconductor chips are mounted to an aluminum nitride baseplate with nickel-plated direct-bonded copper pads for die attach and wire-bonding. The on-state I-V curves (Fig. 8) for each switch shows the typical MOSFET family of curves with a 0.3 V offset due to the Si Schottky barrier. A $V_{DS,ON}$ of 5 V is observed at 100 A with 20 V on the gate. Low leakage blocking is maintained out to 10 kV and shown to be stable at elevated temperature for several thousand hours (Fig. 9). Double pulse switching of 100 A

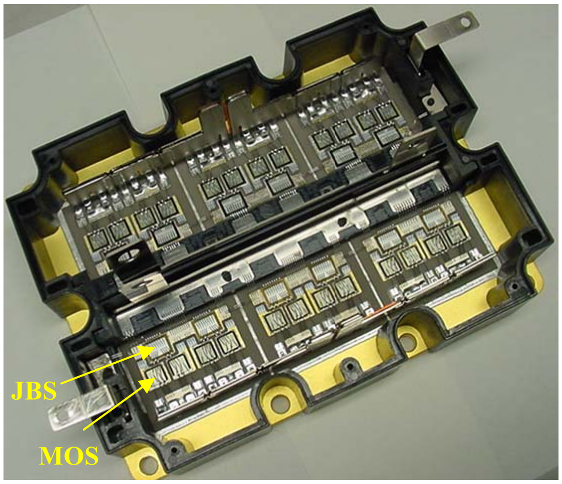

Figure 7. Internal view of the 10 kV, 120 A SiC half H-bridge MOSFET module shows the 12 SiC MOSFETs and 6 SiC JBS diodes used for each switch.

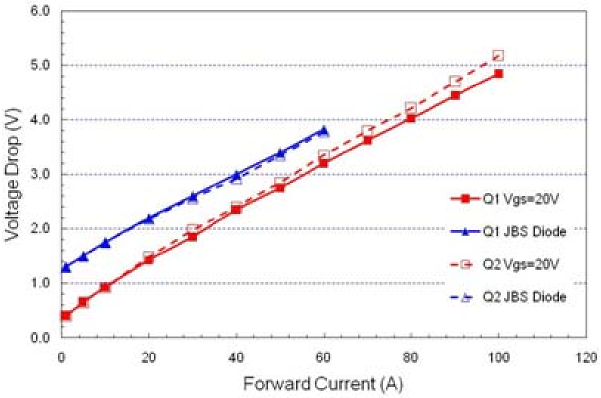

Figure 8. On-state characteristics of Q1 and Q2 switches showing 100 A operation at $V_{DS,ON}$ = 5 V.

and 5 kV shows extremely fast transition times of less than 200 nsec for both the turn-on and turn-off transients (Fig. 10). Despite the large number of paralleled parts, the devices exhibit stable sharing in static and dynamic testing.

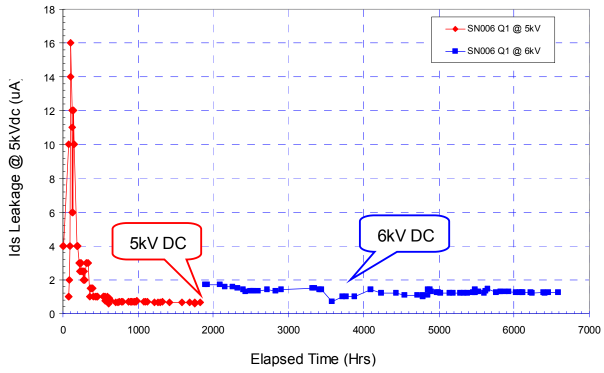

Figure 9. SiC power modules demonstrate stable, low leakage operation in the off-state (5 kV in red and 6 kV in blue) at 125°C.

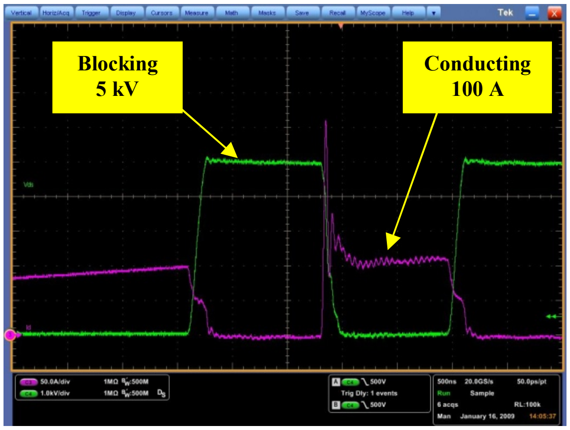

Figure 10. Double pulse switching 5 kV and 100 A using the upper switch in the 10 kV, 120 A SiC half H-bridge MOSFET module.

IV. 1 MVA SOLID STATE POWER SUBSTATION

The ultimate test of viability in any new power electronics technology is its effect on actual systems. In this case, the 10 kV modules have enabled the design and demonstration of a 13.8 kV to 465/√3 V, single phase SSPS rated at 1 MVA full power. The SSPS is a 4 stage, AC – AC, soft-switched converter (Fig. 11) that steps the voltage at 20 kHz using a compact nano-crystalline transformer to facilitate a 75% reduction in weight and a 50% reduction in size over conventional 60 Hz analog transformers of the same power rating. At 855 kVA operation, the SSPS performs at 97% efficiency with the 10 kV SiC modules efficiently running only a few degrees warmer than the background coolant temperature of 25°C.

V. CONCLUSION

High current half H-bridge modules based on 10 kV SiC MOSFETs and JBS diodes have been successfully demonstrated with outstanding static, dynamic, and long-term performance. These state-of-the-art SiC modules are at the heart of a novel solid state transformer technology that enables a medium voltage SSPS which meets the basic specifications of analog transformer technology while providing the benefits of being a digital, multi-tap platform with substantial reduction in size and weight. The successful demonstration of this Mega-Watt class power electronics building block indicates that SiC power devices are poised to assume a prominent role in the development of future high frequency, medium voltage systems where size and weight reductions are critical design criteria

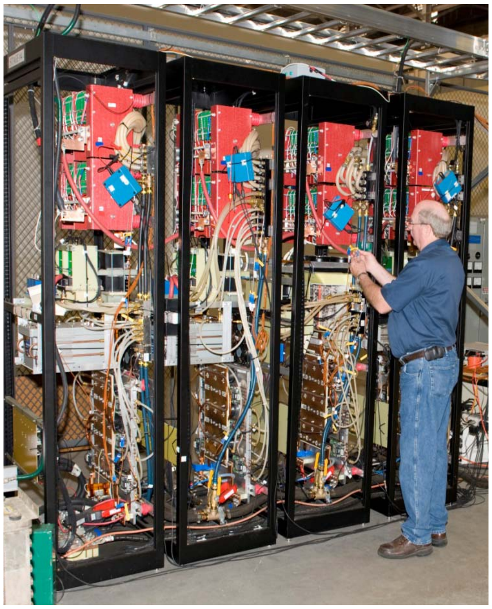

Figure 11. SiC enabled 13.8 kV to 465/√3 V, 1 MVA SSPS that is half the size and one-fourth the weight of a comparable analog 60 Hz transformer.

ACKNOWLEDGMENT

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