# Roadmap for Megawatt Class Power Switch Modules Utilizing Large Area Silicon Carbide MOSFETs and JBS Diodes

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***Abstract* -- Recent dramatic advances in the development of large area Silicon Carbide (SiC) MOSFETs along with their companion JBS diode technology make it possible to design and fabricate high power SiC switch modules. An effort underway by the Air Force Research Laboratory has lead to the development of a 1.2kV/100A SiC dual switch power module capable of operating at a junction temperature of 200°C. Two additional efforts are set on achieving the megawatt goal. An effort by the Army Research Laboratory is focused on 1.2kV modules to be used for traction and power conversion applications. The highest power 1200V all-SiC dual switch power modules produced is capable of 880 amps. A DARPA effort to develop a solid state power substation has produced a 10kV/50A SiC dual switch power module. Higher current modules in both voltage ratings have been designed. These SiC MOSFET modules represent the next level of integration for SiC power devices. This is a critical technical milestone in the progression toward highly reliable, high efficiency, power systems. This technology is relevant in the current energy-conscious environment and will translate to significant energy savings for hybrid and electric vehicles, solar power and alternative energy system inverters, and industrial motor drives.**

***Index Terms* – MOSFET Switches, Power Conversion, Power MOSFET, SiC**

## I. INTRODUCTION

With increasing global emphasis on energy efficiency, improved power devices are critical to the development of the next generation of power systems. Increasing the efficiency of power conversion systems produces multiple benefits. Increasing the efficiency of a system has the obvious benefit of increasing the power output of the system, and it also has the benefit of reducing the amount of waste heat being generated, leading directly to a reduction in the size, weight and complexity of the cooling system. Further decreases in size and weight can be achieved by operating the system at a higher frequency, thereby reducing the number and mass of passive components.

SiC, a wide bandgap semiconductor material, has an electric-field breakdown capability that is ten times that of silicon and also has excellent thermal conductivity. SiC is also a robust material since it is both physically hard and maintains its properties at extremely high temperatures.

When properly designed and fabricated, a power device based on SiC will result in a device with superior characteristics compared to its silicon counterpart. The device characteristics are low conduction losses, low switching losses, higher voltage operation, high temperature operation and the ability to operate at high current density for short periods (surge). Depending on the device type and the specific design, the device characteristics can be optimized to suit the system requirements. SiC power devices, when used in a system, will allow the system to operate at higher efficiency. The silicon carbide power devices available today have been shown to outperform their silicon counterparts [1, 2, 3].

## II. LARGE AREA SIC DEVICES AND MODULE CONSIDERATIONS

Recent advances allow the fabrication of large area SiC power devices. The largest single chip device fabricated in SiC to date is a 180A/4.5 kV PiN Diode [4]. This device has a die size of 1.5 cm x 1.5 cm. The availability of large area SiC chips does not mean they are cost effective for power module applications. As in silicon, the die cost increases exponentially as the device size is increased due to reduced yield and a decrease in the number of devices that can fit on a wafer. As an example, a 100A silicon chip costs 2.5 times that of a 50A chip and a 200A chip cost 5.5 times that of a 100A chip [5]. This is one reason it is common to find multiple die paralleled in a power module. Another reason to use smaller die is to increase reliability by reducing the thermal stress due to thermal coefficient of expansion (TCE) mismatch between the chip and the substrate. Increasing the number of die in a module also increases the assembly cost and decreases the module yield. Care must be taken not to offset the chip cost savings with increased module assembly cost. Due to the higher material and processing cost associated with SiC power devices, the cost to die size relationship is more pronounced for SiC. This is the main reason SiC power modules parallel additional lower current die than what is common in silicon based power modules.

Unlike silicon IGBTs and fast recovery diodes, SiC MOSFETs and SiC JBS diodes are easily paralleled due to their positive coefficient of on-resistance with temperature. Due to this, no matching of device on-state voltage drop is required when paralleling the SiC devices.

Industry has invested many years solving the issues associated with paralleling many power semiconductors in a power electronic module. The focus with the SiC module is to combine the SiC power devices with the best module materials and processes to develop best in class modules.

## III. HIGH TEMPERATURE MODULE

The SiC module shown in Fig. 1 was developed under contract from the Air Force Research Lab (AFRL) to be utilized in inverters that drive the flight control actuators on combat aircraft. The operating environment for this module requires high temperature operation while maintaining low losses. The module is a dual switch configuration (see DUT section in Fig. 6) with a voltage rating of 1200 volts and a current rating of 100 amps. It is capable of operating at a junction temperature of 200°C which is a 50°C increase over the operating temperature of silicon based power modules.

To decrease development time the module design is based on the Powerex silicon IGBT module CM100DY-24NF. Since the silicon IGBT module also has a 1.2kV/100A rating it provides a convenient benchmark for testing the SiC module.

Fig. 1. External view of 1.2kV/100A, all-SiC Half H-Bridge power module.

Two variations of the module were produced. Version A, shown in Fig. 2, uses five 4.7mm x 4.7mm SiC MOSFET die and three 4mm x 8.2mm SiC JBS diode die in parallel for each switch to achieve the 100 amp current rating. Each SiC MOSFET has a nominal current rating of 25A and the SiC JBS diode has a current rating of 50A. Version B of the module, shown in Fig. 3, uses two 7mm x 8mm SiC MOSFET die and two 5.62mm x 5.62mm SiC JBS diode die in parallel for each switch to achieve the 100 amp current rating. Each SiC MOSFET has a nominal current rating of 80A and each SiC JBS diode has a current rating of 50A.

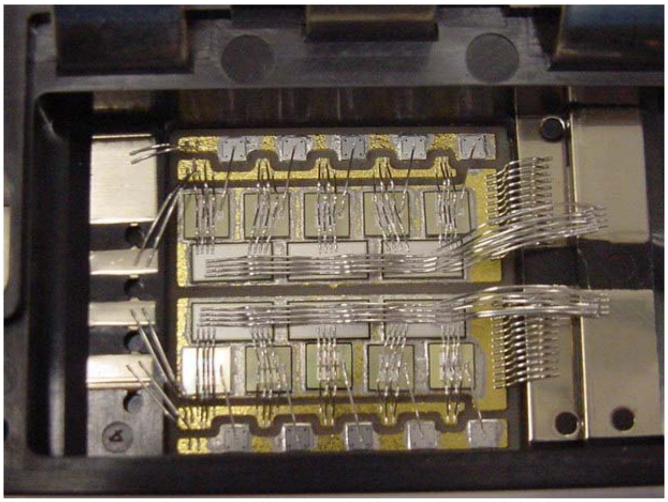

Fig. 2. Internal view of Version A, 1.2kV/100A SiC module showing five 25A SiC MOSFETs and three 50A SiC JBS diodes per switch.

Both versions of the module share a common baseplate, terminal and housing design. An important consideration in any airborne application is weight. To reduce the weight of the power module a graphite fiber reinforced copper alloy metal matrix baseplate was used in place of the standard copper. This resulted in a 32% weight reduction of the baseplate, dropping from 144 grams for the copper version to 98 grams for the metal matrix version. The effect of the base plate change was a 14% reduction in overall module weight.

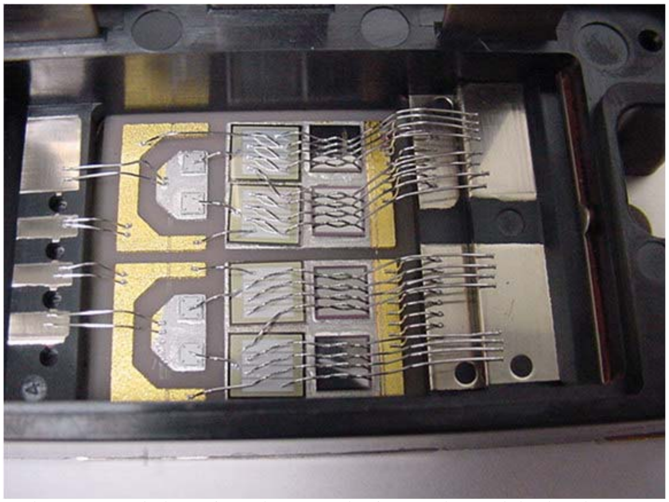

Fig. 3. Internal view of Version B, 1.2kV/100A SiC module showing two 80A SiC MOSFETs and two 50A SiC JBS diodes per switch.

To improve the thermal performance both module designs use direct bonded copper (DBC) aluminum nitride as the substrate material. Aluminum nitride with a thermal conductivity of 210 W/m-K is a significant improvement over the 20 W/m-K of the commonly used Alumina substrate material.

The Version B module design using two MOSFETs and JBS diodes per switch has a simplified chip and wire bond layout resulting in lower package parasitic resistance, lower parasitic inductance, and lower $R_{DS(ON)}$ compared to the Version A design.

The thermal conductivity of SiC is much higher than that of silicon, 3.7 W/cm K for SiC compared to 1.3 W/cm K for silicon; this indicates that SiC should have a thermal impedance advantage in the module. The thermal impedance is also dependent on the total chip area and the total SiC chip area is normally less than the silicon chip area due to the SiC having lower specific on-resistance. For the SiC Version B module the thermal impedance is 0.12°C/W, which is a reduction of 37% over the 0.19°C/W of the silicon IGBT module CM100DY-24NF.

The total power dissipation of a module switch is calculated by dividing the temperature difference between the maximum device junction temperature and the module case temperature by the thermal impedance. Assuming the case temperature is held to 25°C, the total power dissipation of one switch in the silicon IGBT module is 658W. Due to the increase of the junction temperature in the SiC MOSFET module to 200°C and the decrease in thermal impedance, the power total power dissipation of one switch in the SiC module is 1458W. This 220% increase in total power dissipation is a powerful example of the performance advantages of SiC MOSFET modules.

## IV. 100A MODULE DC CHARACTERIZATION

DC characterization of the Version A SiC module at 100A with a gate voltage of 20V showed an on-state voltage drop of each switch to be 1.36V at 25°C. The on-state voltage increased slightly at 150°C to 1.63V. Accurate measurement of the switching performance was not possible due to excessive oscillation. This oscillation was originally attributed to the chip layout and long wire bond lengths utilized in the Version A module but later it was discovered that much of it was caused by noise susceptibility of an optocoupler used on the gate drive circuit. Due to Version B of the module being completed before the gate drive issue was resolved, the Version A module was not fully characterized.

Fig. 4 compares the DC on-state characteristics of the Version B SiC module to the silicon IGBT module at junction temperatures of 25°C and 150°C. The on-state characteristics are also shown for the SiC module at a junction temperature of 200°C. Measurements were taken with a gate voltage of 20V. At 25°C the on-state voltage at 100A for the silicon module is 2.3V compared to 1.2V for the SiC module or a reduction of 48%. At 150°C the on-state voltage at 100A for the silicon module is 2.6V compared to 1.5V for the SiC module or a reduction of 42%. Even at 200°C the on-state voltage at 100A of the SiC module is 1.9V which is still lower than the silicon IGBT module at 25°C. Since the on-resistance of the SiC MOSFET is linear and the SiC MOSFET does not have a knee voltage like the IGBT, the on-state advantage of the SiC module is greater at lower currents. For example at 150°C the on-state voltage at 40A for the silicon module is 1.7V compared to 0.6V for the SiC module or a reduction of 65%. The results indicate that over the whole temperature and current range the SiC MOSFET has a significant on-state advantage over the silicon IGBT module.

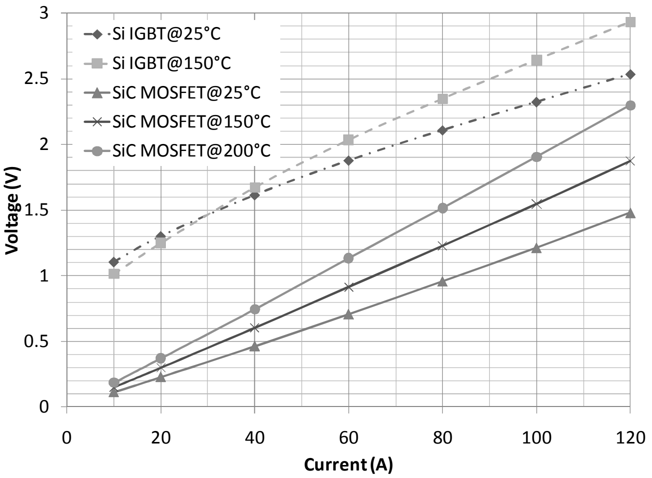

Fig.4. Comparison of on-state voltage between the 1.2kV/100A SiC module and the equivalently rated Si IGBT module (CM100DY-24NF).

## V. 100A MODULE SWITCHING CHARACTERIZATION

A major advantage the SiC MOSFET has over other device types which are being developed in SiC is that it is a normally-off voltage controlled device. The voltage drive levels of 0V to -5V for the off-state and +15V to +20V for the on-state of the SiC module are similar to silicon IGBTs and MOSFETs. As seen in Fig. 5 the gate charge of the SiC module is also similar to the silicon IGBT module. The similar gate voltage and gate charge requirements indicate that the SiC MOSFET module can be driven with the same gate drive techniques that are presently used for driving silicon IGBTs and MOSFETs.

Fig. 6 shows the circuit schematic of the inductive load switching test setup. In this configuration both the upper and lower switches of the module are used during testing. Testing with both switches in the circuit provides results that are representative of what would be seen in applications.

Fig. 7a shows turn-on waveforms of the SiC MOSFET module and the silicon IGBT module at 150°C. Evident in the waveforms is the large turn-on current peak of the silicon IGBT which is caused by the reverse recovery of the upper switch anti-parallel diode. Also seen in the waveform is ringing of the voltage and current waveforms of the SiC MOSFET module. This ringing was also observed in the gate voltage and may be partially attributed to the long wire bond lengths used on the gate and source sense connections within the module. Fig. 7b shows turn-off waveforms of the SiC MOSFET module and the silicon IGBT module at 150°C.

Evident in the waveforms is the turn-off current tail of the silicon IGBT.

Table I shows the turn-on, turn-off and total switching energy for the silicon IGBT module and the SiC MOSFET module at 25°C. The total switching energy is reduced by 3 mJ or 20% with the SiC MOSFET module. The 150°C turn-on, turn-off and total switching energy for the silicon IGBT module and the SiC MOSFET module is shown is Table II. At 150°C the total switching losses are further reduced using the SiC MOSFET module by 8.6 mJ or 41%. While this switching loss reduction is impressive, it is possible to improve this reduction with the SiC MOSFET module. The SiC MOSFET has low transconductance when compared with silicon switches. Due to this, the turn-on and turn-off times and the switching losses of the SiC MOSFET are closely coupled to the transition time of the gate voltage. Driving the gate harder, by lowering the external gate resistance will directly result in lower switching losses.

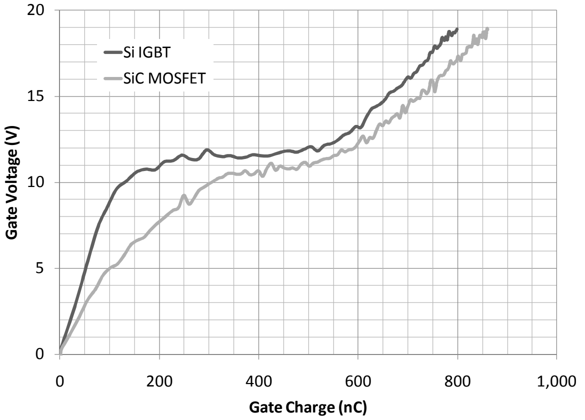

Fig.5. Gate bias as a function of total gate charges measures at a drain current of 100A and a drain voltage of 800V for the 1.2kV/100A SiC module and the Si IGBT module (CM100DY-24NF).

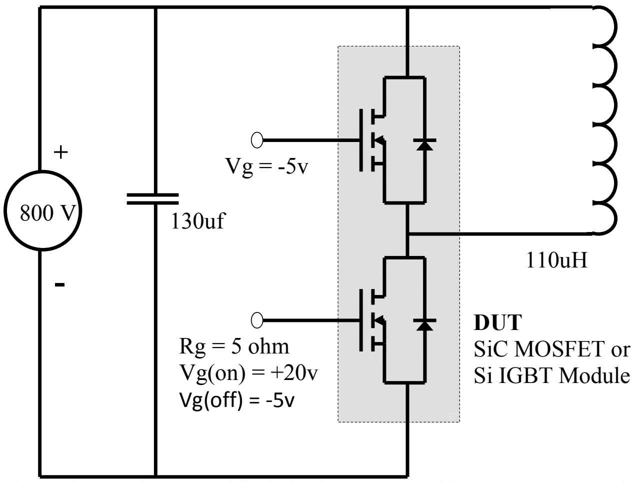

Fig.6. Circuit schematic of the inductive load switching test setup used for comparison of switching performance of the 1.2kV/100A all SiC module and the Si IGBT module (CM100DY-24NF).

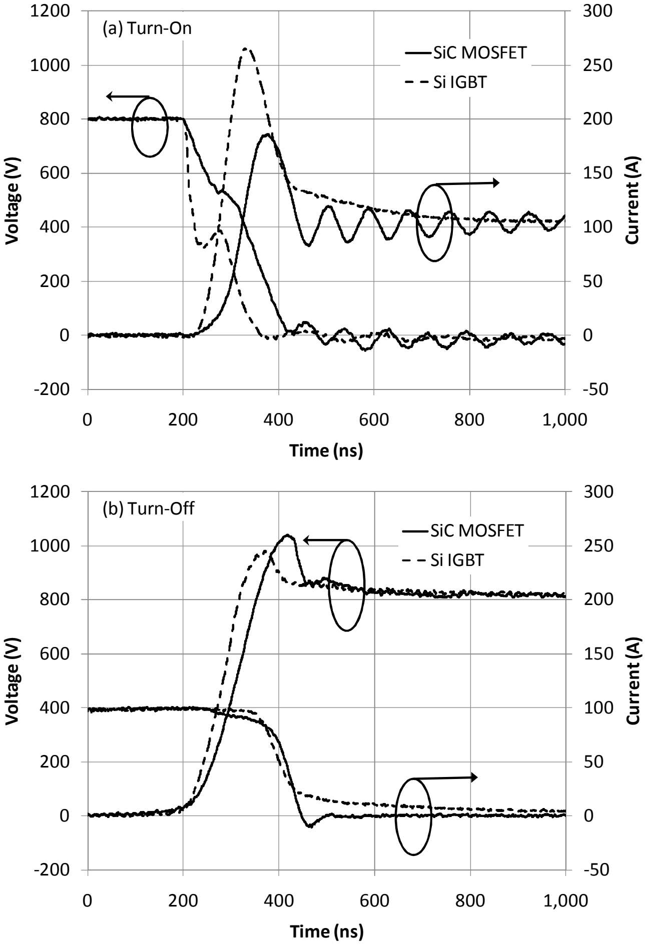

Fig.7. (a) Turn-on and (b) turn-off waveforms at 150°C of the 1.2kV/100A SiC module and the Si IGBT module (CM100DY-24NF).

Table I
Switching Energy comparison at 25°C

| Module | Eon (mJ) | Eoff (mJ) | Etotal (mJ) |
|---|---|---|---|
| Si IGBT | 2 | 12.6 | 14.6 |
| SiC MOSFET | 2.7 | 8.9 | 11.6 |

Table II
Switching Energy comparison at 150°C

| Module | Eon (mJ) | Eoff (mJ) | Etotal (mJ) |
|---|---|---|---|
| Si IGBT | 3.5 | 17.3 | 20.8 |
| SiC MOSFET | 2.5 | 9.7 | 12.2 |

## VI. HIGH CURRENT 1200V MODULES

A high current 1.2kV SiC MOSFET module has been developed by the Army Research Laboratory to be used for traction and power conversion applications. The dual switch module is based on the Powerex Mega Power Dual module family. The module uses a parallel combination of eleven of the 80A MOSFETs and eleven of the 50A JBS diodes per switch to achieve a nominal current rating of 880A. Fig.8 shows the internal layout of the module. The combination of the voltage and current rating make this one of the first SiC modules with a power rating of 1MW. Fig.9 shows the on-state characteristics of the 1.2kV/880A SiC MOSFET module. At 880A the module has an on-state voltage of 1.9V. Even at 1000A, the on-state voltage of 2.26V of the SiC MOSFET module compares favorably with what is typical of silicon IGBTs. Additional DC and switching characterization is underway at the US Army Research Laboratory and will be published in the near future.

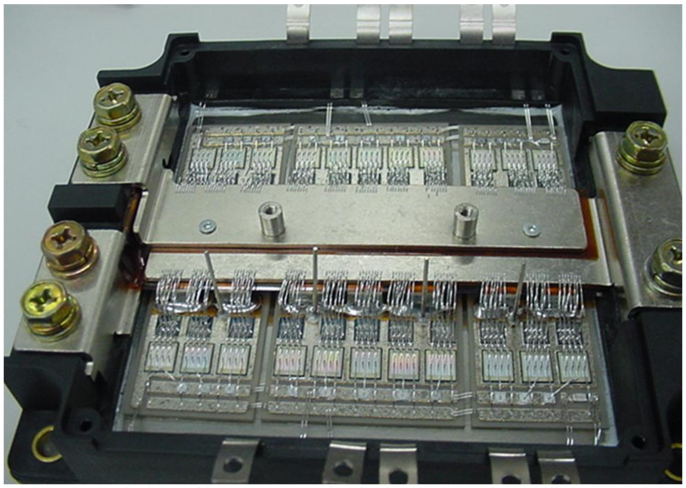

Fig.8. Internal view of large 1200V SiC dual switch module utilizing 11 of the 80A SiC MOSFETs and 11 50A SiC JBS diodes per switch.

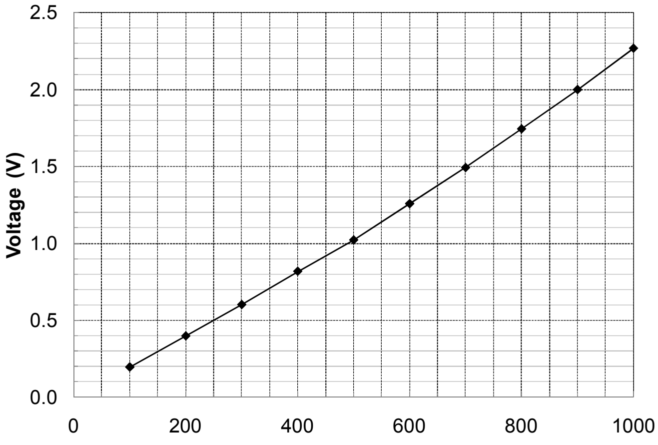

Fig.9. Room temperature on-state characteristics of the large 1200V/ 880A dual switch module with a gate voltage of 20V.

The 1.2kV/880A SiC dual switch module is intended as a stepping stone to a higher current SiC MOSFET module. A module is in design that will utilize twenty two of the 80A SiC MOSFETs and eleven 100A SiC JBS diodes per switch. The 1.2kV/100A SiC JBS diode is 7mm x 9 mm. This 1.2kV SiC MOSFET module should have a nominal current rating of 1600A. A sketch of the chip layout concept is shown in Fig. 10. Using this concept it will be possible to fit the chips required for the 1600A module into the module housing used in the 880A/1.2kV module with only a substrate redesign.

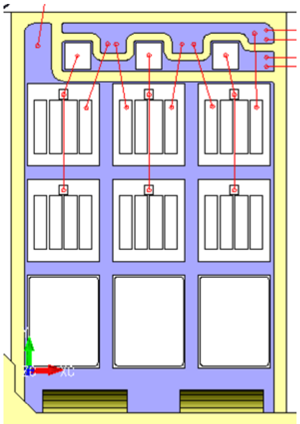

Fig.10. Chip layout concept for 1600A SiC module which will use twenty two 80A SiC MOSFETs and eleven 100A SiC JBS diodes per switch.

## VII. 10kV Module

A DARPA effort to develop a solid state power substation has produced a 10kV/50A SiC dual switch power module that is capable of switching at 20 kHz. The module consists of five 8.1mm x 8.1 mm 10kV/10A SiC MOSFET die and five 8.3mm x 10.6 mm 10kV/10A SiC JBS diode die paralleled per switch. The on-state voltage of the SiC JBS diode is higher due do the increased on-resistance of the 10kV device. A silicon Schottky diode is placed in series with the SiC MOSFET to ensure the SiC MOSFET body diode is not turned on when the SiC JBS diode is conducting. Fig. 11 shows how the silicon Schottky diode is incorporated into the dual switch configuration. Two of the silicon Schottky diode die are paralleled in each switch.

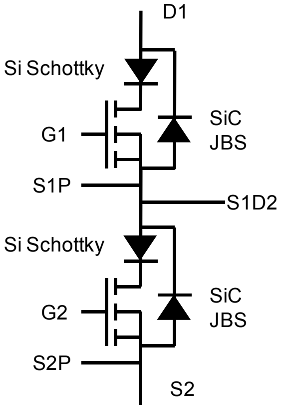

Fig.11. 10kV/50A SiC MOSFET dual switch module schematic showing location of silicon Schottky diodes.

Fig. 12 is an internal view showing the chip layout of one switch of the 10kV/50A SiC MOSFET dual switch module. Fig. 13 shows the on-state characteristics of the SiC MOSFET module at 25°C with gate voltages of 15V and

20V. The 0.2V offset in the on-state voltage is due to the knee voltage of the silicon Schottky diode. At the rated 40A with a gate voltage of 20V, the on-state voltage of the module is 4.1V. This level of performance at 10kV is unparalleled with silicon technology.

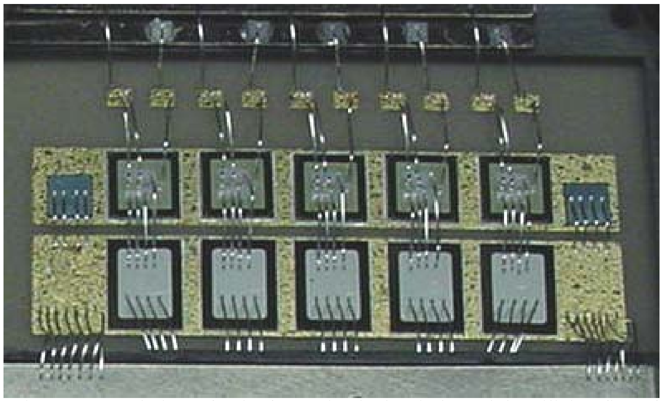

Fig.12. Internal view of 10kV/50A SiC dual switch module utilizing five of the 10A SiC MOSFETs and five 10A SiC JBS diodes per switch.

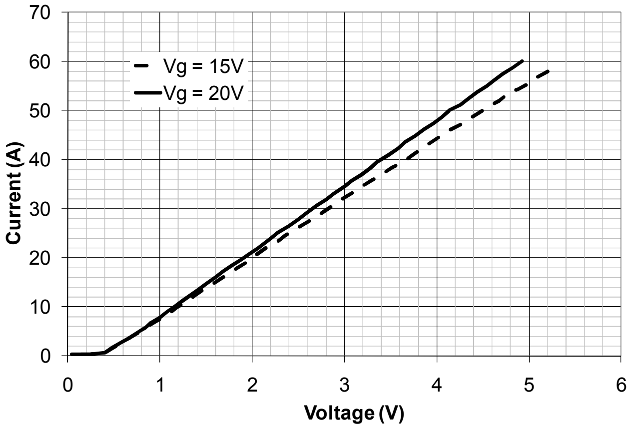

Fig.13. Room temperature on-state characteristics of the 10kV/ 50A dual switch module at gate voltages of 15V and 20V.

## VIII. SUMMARY

This new power switch module technology based on SiC MOSFETs and JBS diodes has higher total power capability, lower conduction losses and lower switching losses than available IGBT modules. The SiC MOSFET modules are voltage driven, normally-off devices that have drive requirements similar to the silicon IGBT modules they are targeted to replace. This makes the SiC module a drop-in replacement for silicon IGBT and MOSFET modules in most applications. The SiC power switch module will be an enabling technology for next generation power systems. These modules will lead to smaller, lighter-weight systems with reduced cooling requirements and increased reliability.

## ACKNOWLEDGMENT

The 100A/1.2kV high temperature module work is supported by the Propulsion Directorate of the Air Force Research Laboratory (AFRL) under contract # FA8650-07-C-2780, monitored by Dr. James Scofield.

The high current 1.2kV module work was supported by the Sensors and Electron Devices Directorate of the U.S. Army Research Laboratory (ARL), through the Cooperative Agreement W911NF-04-2-0022, directed by Charles Scozzie.

The 10kV module work was supported by DARPA and Sharon Beermann-Curtin through contract N00014-05-C-0202 monitored by Dr. Harry Dietrich.

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