Status of the DARPA WBST High Power Electronics Program in SiC Device Development and Technology Transition †

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Abstract: *The emergence of High-Voltage, High-Frequency (HV-HF) Silicon-Carbide (SiC) power devices is expected to revolutionize industrial and military power generation, transmission, and distribution systems. The DARPA Wide Bandgap Semiconductor Technology (WBST) High Power Electronics (HPE) program is spearheading the development of this HV-HF SiC power semiconductor technology. This paper describes recent progress of the WBST HPE program in device development and in circuit performance demonstrations of the devices. The paper also discusses the planned program to demonstrate a prototype 2.75 MVA Solid State Power Substation (SSPS) using the HV-HF SiC power device technology and introduces the planned projects to establish reliability and manufacturability of the materials, devices, and packages for the HV-HF SiC power devices.*

Keywords: Silicon-carbide; wide band-gap; power semiconductor; high-voltage; Solid State Power Substation.

Introduction

The Defense Advanced Research Projects Agency (DARPA) has made a significant investment to accelerate the development and insertion of the High-Voltage, High-Frequency (HV-HF) power devices necessary for improving military and industrial electrical power systems. A new class of power devices based on Silicon Carbide (SiC) is now emerging for future power electronic systems. Compared to silicon-based semiconductors, the intrinsic properties of SiC allow power conversion at higher voltages and frequencies enabling lighter and smaller switches with improved power quality. Hence, the space saving enables integration of advanced and tactical functionalities in future more electric based military platforms.

Significant advances in the quality of SiC substrates and epitaxial layers were made during the first phase of the DARPA Wide Bandgap Semiconductor Technology (WBST) High Power Electronics (HPE) Program to support the development of high voltage power devices.

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The goal of the ongoing second phase of the WBST-HPE program is to develop 10 kV, 100 A, 20 kHz class power semiconductor devices to enable future electric ships, more electric aircraft, and all electric combat vehicles [1]. The advances in material and fabrication technology made in the WBST-HPE first and second phase have led to the development of HV-HF power devices with 10 kV, 20 kHz power switching capability.

As a result of the successful demonstration of SiC material and device technology in the WBST-HPE phase-one and phase-two programs, several new programs have recently been initiated: DARPA recently announced a third phase of the WBST-HPE program to perform innovative research in the area of HV-HF switch-mode power conversion [2]. The goal of the phase-three program is to demonstrate a 2.75 MVA prototype Solid State Power Substation (SSPS) for future naval aircraft carriers with advanced capabilities and significant reduction of the weight and volume of existing systems. The Office of Naval Research (ONR) Science and Technology Office of Transition also announced two Navy ManTech projects; one to address the module packaging technology for the 10 kV, 100 A, 20 kHz class power semiconductor devices and the other to address the associated SiC material reliability and manufacturability for HV-HF devices [3].

The purpose of this paper is to describe recent progress of the DARPA WBST-HPE phase-two program in development and circuit performance demonstrations of these devices. This paper also discusses the planned program to demonstrate a prototype 2.75 MVA Solid State Power Substation (SSPS) using the HV-HF SiC power device technology and discusses the planned Navy ManTech projects to establish reliability and manufacturability of the materials, devices, and packages for the SiC power devices.

HPE Program Objectives

The U.S. Navy plans advanced and integrated power electronics in future platforms as the means to achieve transformational capability in weapons delivery. Power conversion equipment developed using SiC technology is projected to significantly reduce the workload and maintenance requirements for current and future carriers and is considered a critical step in achieving US Navy CVN-21 program compliance with key performance parameters for weight reduction and ship stability.

As part of a Memorandum of Agreement (MOA)between DARPA, the Office of Naval Research (ONR), and Program Executive Office for Carriers (PEO-Carriers, NAVY) regarding the use of Wide Band Gap (WBG) Semiconductors for Ship's High Power Distribution, a multi-year program has been established to focus the research and development efforts. The development of a 2.75 MVA solid-state substation has been identified as a first demonstration vehicle.

The SiC power device technology transition plan subject of the MOA includes the WBST-HPE phase-three program. The goals and benefits of this research are described in the DARPA Broad Area Announcement (BAA-06-30) as follows [2]:

"In November of 2004, a Memorandum of Agreement was signed by the Navy and DARPA to develop a silicon carbide-based, high frequency, SSPS for future Naval Aircraft Carriers. The electrical distribution system being designed for the next generation of Aircraft Carriers employs 13.8 kV AC power distribution that is stepped down to 4,160 V AC or 465 V AC by using large (5,500 kg and 10 m^3) 2.75 MVA 60 Hz conventional transformers. The desired advanced power electronic system under this effort will demonstrate a silicon carbide based SSPS that converts the distributed 13.8 kV AC power down to 465 V AC at the same total power level (2.75 MVA) as the current system.

The component level benefit of using a high frequency solid state transformer over the conventional transformer is a significant reduction of weight and volume. System benefits of the high frequency, solid state topology include, but are not limited to, voltage regulation, over-current protection, power factor correction, improved power quality, frequency regulation and frequency changing, overload and surge protection, and potential removal of circuit breakers, which currently add weight and take up space, allowing the system to sag during power faults."

In order to support the packaging reliability and manufacturing needs of the WBST-HPE program subject to the MOA, a Navy ManTech Manufacturing Technology Program entitled "Manufacturing and Packaging of Power Systems for DDG-1000 and Carrier" was established. The project is being performed by the American Competitiveness Institute (ACI) Electronics Manufacturing Productivity Facility (EMPF). The goal of this project as defined in the 2007 Navy ManTech Project Book [3] is to *"identify and demonstrate a packaging methodology that is applicable to current power devices / modules as well as readily adaptable to future power device technology. An evaluation of potential materials that can be used in the design and development of a solid state transformer was also included in this project."*

In order to support the SiC device and materials reliability and manufacturing needs of the WBST-HPE program subject to the MOA, a Navy ManTech Manufacturing Technology Program entitled "High-Power SiC PiN Diode Manufacturing" was established. The project is to be performed by Penn State University Electro-Optics Center (EOC) with Cree Inc. as a subcontractor producing the materials and devices. The objective of this project as defined in the 2007 Navy ManTech Project Book [3] is to *"address the manufacturing issues which presently limit the yield of high-voltage SiC PiN diodes* [for example] *needed for the switching modules of the SSPSs for future Navy ships."*

Status of 10 kV SiC Diodes

Substantial progress has been made thus far in the WBST-HPE phase-two program in demonstrating PiN diodes with excellent breakdown voltage and leakage current characteristics, improved on-state voltage, and improved forward bias degradation performance [4]. Although the switching speed of 10 kV PiN diodes is currently too slow for 20 kHz hard switching applications such as the SSPS, progress has been made in improving the speed and also in developing 10 kV SiC Junction Barrier Schottky (JBS) diodes. For 10 kV devices, SiC PiN diodes tend to have higher peak current density capability and higher continuous current density capability at high temperature, whereas JBS Schottky diodes tend to have lower reverse recovery charge enabling higher frequency operation and have a positive temperature coefficient of on-voltage enabling paralleling of large area die.

Figure 1 shows the reverse leakage current and breakdown characteristics for a 0.2 cm^2 PiN diode produced in WBST-HPE phase-two. The characteristics of Fig. 1 demonstrate a sharp breakdown voltage above 12 kV (1 mA/cm^2) with extremely low leakage current below 10 kV (less than 300 nA) for all temperatures from 25 ºC to 200 ºC. The positive temperature coefficient of breakdown voltage suggests uniform avalanche multiplication across the chip.

Figure 2 shows the forward conduction characteristics of a WBST-HPE phase-two PiN diode for temperatures from 25 ºC to 200 ºC indicating the 300 W/cm^2 power dissipation level intersections. This shows that a 0.2 cm^2 device can operate continuously at 20 A (100 A/cm^2) within a package capable of dissipating 300 W/cm^2. The device has a small –14 mV/ºC temperature coefficient at 20 A. This should provide reasonable ability to parallel multiple chips.

Figure 3 shows a comparison of the reverse recovery waveforms at 125 ºC for two different SiC PiN diode designs and a SiC JBS diode, all produced in the WBST-HPE phase-two program. Although the PiN diode reverse recovery charge (area under negative portion of the current waveform) has been improved from device type (a) to device type (b), further improvement is necessary to achieve 20 kHz switching capability. However, the reverse

recovery charge for the JBS diode is suitable for 20 kHz in a 300 W/cm^2 capable package.

A concern with SiC PiN diodes in the past has been forward bias degradation and the associated reduction in conduction area [5]. This has been shown to be due to stacking fault growth nucleated at defects originating in the starting wafer and from processing-induced defects. WBST-HPE phase-two has made significant progress in eliminating these nucleation sites [6] resulting in devices that degrade less than 0.1 V after 1000 hours of operation at full current rating (100 A/cm^2). Figure 4 shows that the conduction area (red region) is also not reduced after the 1000 hours of stress for the non-degrading devices. Previous PiN diodes have conduction area reduction of from 30 % to 90 % [4,5].

Status of 10 kV SiC Switches

Substantial progress has been made thus far in the WBST-HPE phase-two program in demonstrating 10 kV SiC switches. It has been demonstrated that Power MOSFETs are generally suitable for 20 kHz hard switching applications such as the SSPS [4,7]. Phase-two MOSFETs have achieved positive threshold voltage up to 200 ºC resulting in low leakage and high transconductance leading to 30 A/cm^2 continuous and 100 A/cm^2 peak current density capabilities. Progress has also been made in demonstrating SiC IGBT switches. For 10 kV devices, SiC IGBTs tend to have higher peak current density capability and higher continuous current density capability at high temperature, whereas MOSFETs tend to have faster switching times enabling higher frequency operation and a positive temperature coefficient of on-state voltage enabling paralleling of large area die.

Figure 5 shows the blocking characteristics of a WBST-HPE phase two MOSFET for $V_{gs} = 0$ V and a temperature of 25 ºC and 200 ºC. The MOSFET channel current contributes to the low drain voltage leakage current particularly at high temperatures because the threshold voltage decreases with temperature. The low leakage below 10 kV indicates that the threshold voltage is positive for the full temperature range up to 200 ºC.

Figure 6 shows the on-state characteristics at 25 ºC through 200 ºC in steps of 25 ºC for $V_{gs} = 20$ V, indicating the 300 W/cm^2 power dissipation level intersection. This shows that the device can operate at 4 A (30 A/cm^2) for the entire temperature range with less than 300 W/cm^2 heat removal requirements for the package. The positive temperature coefficient results in higher losses at higher temperatures. For higher temperature operation, the pulsed and continuous current capability is reduced and IGBTs would become an attractive alternative to MOSFETs.

Figure 7 shows the MOSFET inductive load turn-off for a clamp voltage of 10 kV, a drain current of 12 A (80 A/cm^2), a gate resistance of 4 Ω, and a temperature of 200 ºC. This indicates a rugged device with a "square" Reverse Bias Safe Operating Area (RBSOA) of 100 % of the blocking voltage and a current of nearly three times the continuous current rating (5 A). The device also switches very rapidly resulting in low switching energy and enabling 20 kHz operation in a package with 300 W/cm^2 heat removal capabilities.

A long-term switching reliability test system was recently developed to evaluate the ability of HV-HF SiC power devices to operate continuously at 20 kHz switching without degradation. Figure 8 shows measured drain voltage and current and inductor current waveforms from this test system using a 10 kV, 5 A SiC MOSFET developed in phase-two. The devices perform as expected without degradation of characteristics. Comparisons were performed with 4.5 kV Si IGBTs operating with 2.8 kV bus voltage. The switching speed was about 20 times slower and the losses 20 times higher with the Si IGBT.

Conclusion

The WBST-HPE phase-two program has made significant progress in demonstrating the SiC device and material technology necessary for 10 kV, 20 kHz power switching capability. DARPA has announced a third phase of this program to demonstrate a 2.75 MVA prototype Solid State Power Substation (SSPS) for future naval aircraft carriers using this device technology. Two Navy ManTech Manufacturing Technology Programs have also been initiated to address the reliability and manufacturability of the materials, devices, and packages for the HV-HF SiC power device technology.

Acknowledgment

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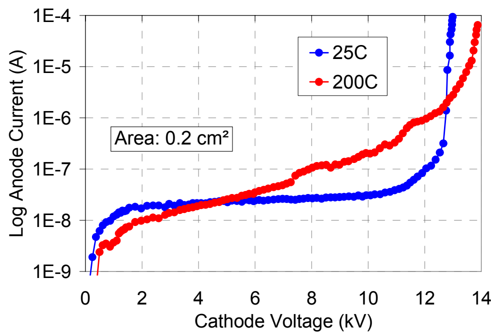

Figure 1. Reverse leakage current versus voltage for a SiC PiN diode at different temperatures.

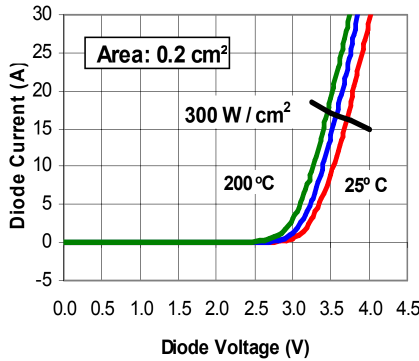

Figure 2. Forward conduction characteristics of a 10 kV SiC PiN diode at 25 °C, 100 °C, and 200 °C.

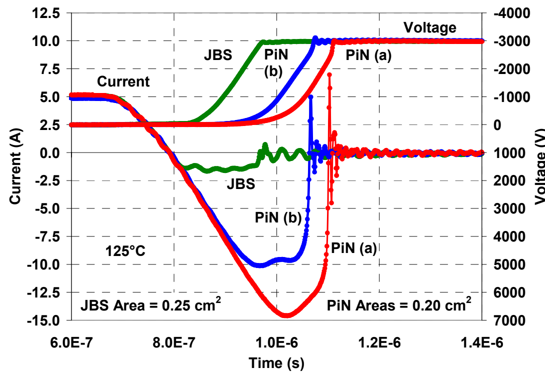

Figure 3. Reverse recovery time for two different 10 kV SiC PiN diodes and a 10 kV JBS SiC diode, all at 125 °C.

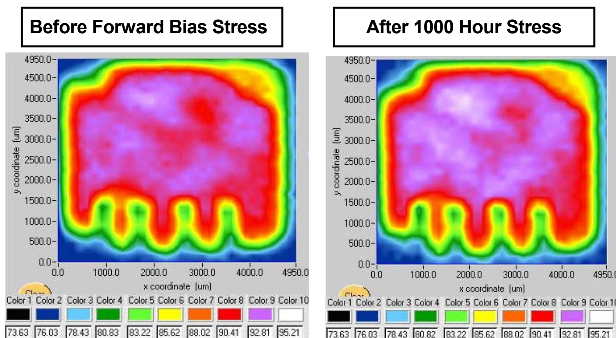

Figure 4. Current uniformity before and after 1000 hours of forward bias stress at 20 A (100 A/cm^2) showing no area reduction.

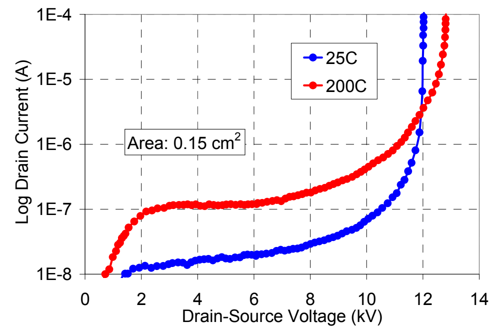

Figure 5. MOSFET drain leakage current at V_{gs} = 0 V at 25 °C and 200 °C indicating low leakage up to 200 °C.

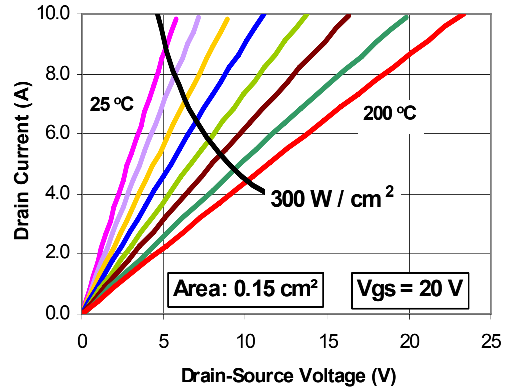

Figure 6. MOSFET on-state characteristics for V_{gs} = 20 V at 25 °C to 200 °C in 25 °C steps indicating 300 W/cm^2 power dissipation level.

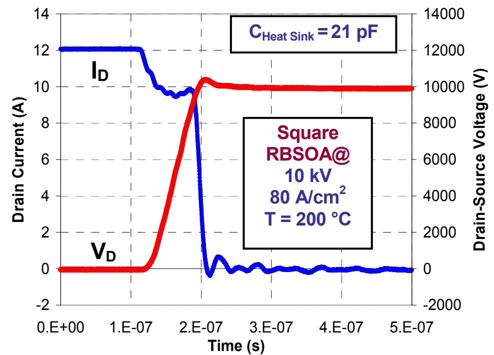

Figure 7. MOSFET inductive load turn-off indicating RBSOA at 100 % blocking voltage and 80 A/cm^2.

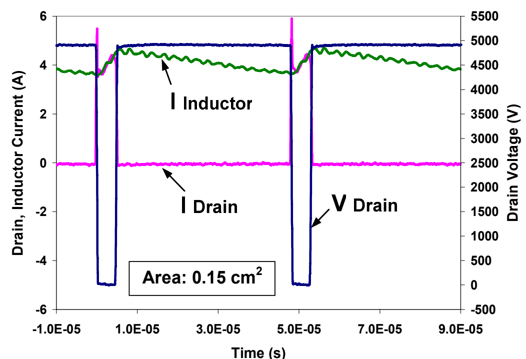

Figure 8. MOSFET drain voltage, drain current, and inductor current waveforms from 20 kHz switching stability test.