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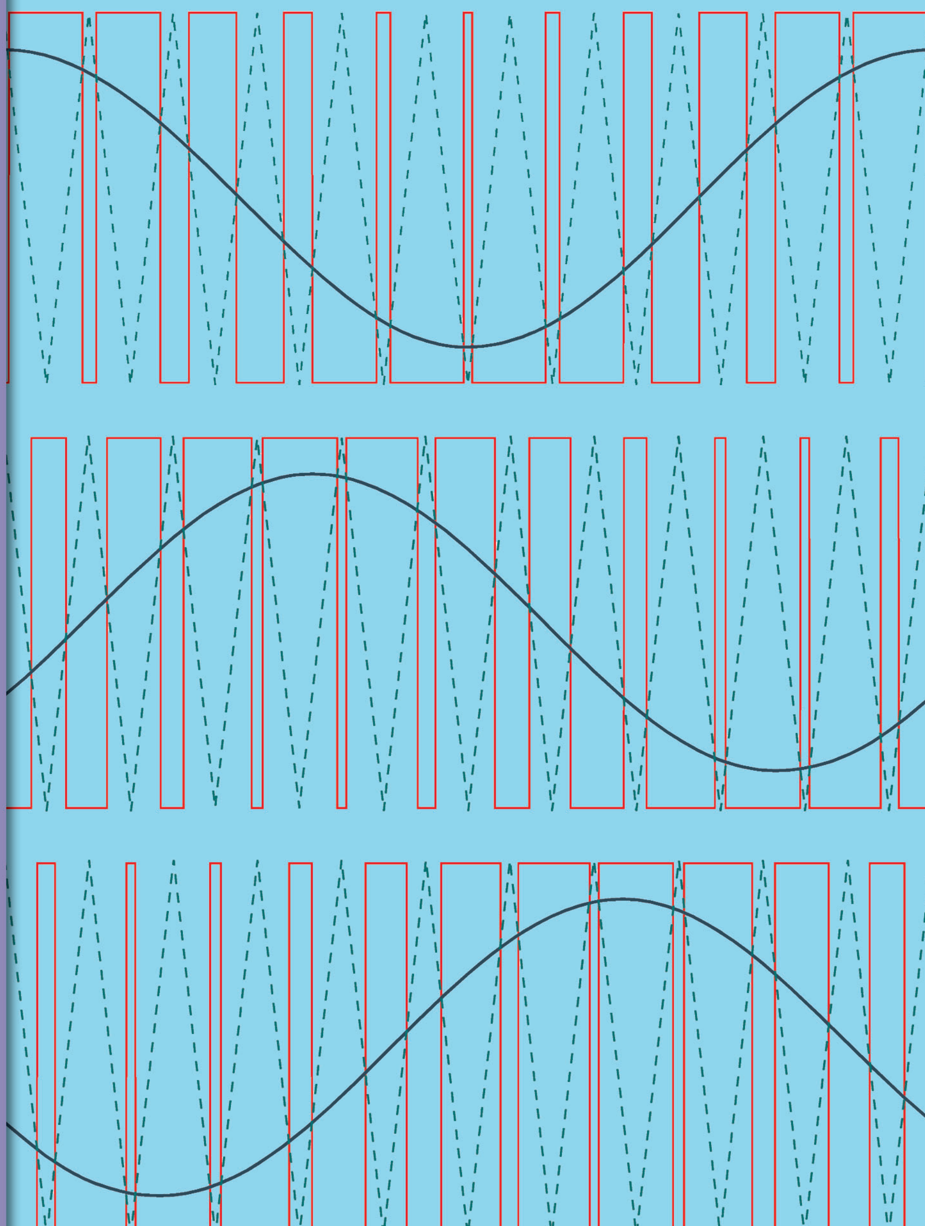

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Emerging Silicon-Carbide Power Devices Enable Revolutionary Changes in High Voltage Power Conversion

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INTRODUCTION

Recent breakthroughs in Silicon Carbide (SiC) material and fabrication technology have led to the development of High-Voltage, High-Frequency (HV-HF) power devices with 10-kV, 15-kHz power switching capability. Programs are underway to demonstrate half-bridge modules with 15-kV, 110-A, 20-kHz capability in the next few years. The emergence of HV-HF devices with such capability is expected to revolutionize utility and military power distribution and conversion by extending the use of Pulse Width Modulation (PWM) technology to high voltage applications.

Wide bandgap semiconductors such as SiC have long been envisioned as the material of choice for next generation power devices [1]. Although wide bandgap semiconductor materials have superior properties, the realization of power device quality substrates and fabrication technologies required overcoming many technical challenges. The rapid advances in single crystal SiC over the last decade have ushered in a new era of wide bandgap power semiconductor devices. In 2004, Dr. Calvin Carter of Cree Inc. received the US National Medal of Technology from President George W. Bush for: “his exceptional contributions to the development of Silicon Carbide wafers, leading to new industries in wide bandgap semiconductors and enabling other new industries in … more efficient/compact power supplies, and higher efficiency power distribution/transmission systems.”

Currently, there are significant efforts underway to accelerate the development and application insertion of the new HV-HF SiC devices needed for commercial and military power conversion and distribution applications. The goal of the ongoing Defense Advanced Research Projects Agency (DARPA) Wide Bandgap Semiconductor Technology (WBST) High Power Electronics (HPE) program directed by Dr. John Zolper is to develop 15-kV class power semiconductor devices enabling future electric ship, more electric aircraft, and all electric combat vehicles. DARPA is particularly interested in developing the power electronics device technology deemed necessary to enable 2.7 MVA Solid State Power Substations (SSPS) for future Navy warships.

The benefits of HV-HF semiconductor technology have also been identified by the Electric Power Research Institute (EPRI) including advanced distribution automation using solid-state distribution transformers with significant new functional capabilities and power quality enhancements. In addition, HV-HF power devices are an enabling technology for alternative energy sources and storage systems. The emergence of HV-HF power devices presents unique opportunities and challenges to the power electronics industry in specifying the device requirements and establishing PWM converter topologies for high voltage applications.

HIGH VOLTAGE POWER CONVERSION APPLICATIONS

Figure 1 shows the application ranges for the majority of power semiconductor devices indicating shaded areas where SiC is likely to have an impact in the near future. Generally the power device market size decreases with increasing voltage and current requirement. Presently the market size for the relatively lower voltage and current **Power Supply** area is several times larger than for all other applications combined with device sales of approximately $5B/year. For higher voltage applications such as **Motor Control** and **Traction**, the device current requirements typically increase as the voltage requirement increases due to the large power requirements in these applications. An exception to these trends is in the power distribution area where the **HV-HF Power Conversion** would require devices for a wide range of current ratings and the market size could be relatively large. However, the HV-HF Power Conversion market has not yet developed due to the 6.5 kV voltage limit and slow switching speed of high voltage Silicon power devices.

Over the last two decades, PWM power conversion technology, with its superior efficiency and control capability, has changed the way power is converted in almost all low and medium voltage power conversions applications from 100 V to 6.6 kV. Due to fundamental limitations of Silicon devices, the on-resistance increases and switching speed decreases as the blocking voltage requirement is increased. The switching speeds in low voltage power supplies are as high as several MHz and decrease to several kHz for high power traction. The higher on-resistance and slower switching speed increase losses and limits applicability of PWM for high power and utility applications.

The developments of Silicon IGBTs over the last decade have enabled high frequency power conversion to be used at increasingly higher power levels. Recently SiC power Schottky diode products have also been introduced that increase switching speed capability by reducing diode reverse recovery loss. It is expected that SiC power devices will continue to aid the evolution of increasing PWM frequency and power levels in the **Power Supply** and **Motor Control** areas as SiC Schottky diode and MOSFET products are introduced with higher voltage and current ratings. Because SiC devices have the capability to increase the voltage beyond that of Silicon into the 10 kV through 25 kV range with much higher switching speed for a given blocking voltage, they provide the revolutionary potential to extend high

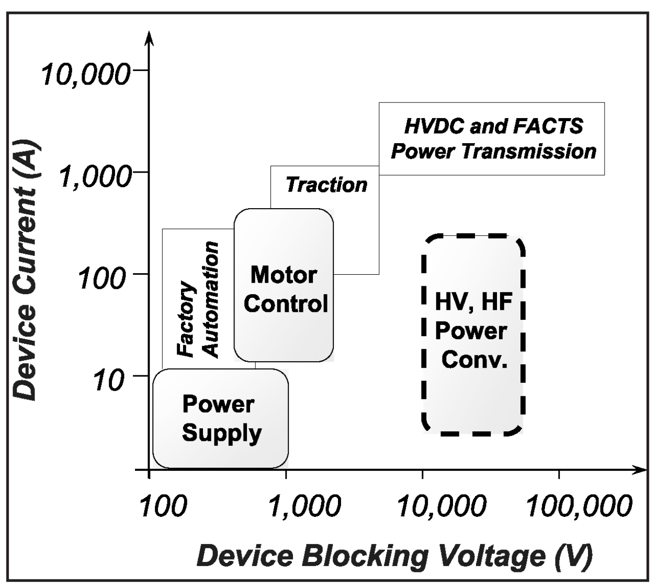

Figure 1. Application ranges for the majority of power semiconductor devices indicating shaded areas where SiC is likely to have an impact in the near future.

frequency PWM switching power conversion into the relatively large volume application area of utility **HV-HF Power Conversion**.

Recent EPRI reports (1001698, 1002159 – see www.epri.com for abstracts) concluded that a solid-state distribution transformer, referred to as the Intelligent Universal Transformer (IUT), would add significant new functional capabilities and power quality enhancements to those available from conventional copper and iron transformers. The IUT is expected to be a cornerstone device in advanced distribution automation (ADA). A more recent EPRI report (1009516) identified SiC power devices as the solution for the HV-HF semiconductor devices needed for the IUT and estimated that **HV-HF Power Conversion** could represent a relatively large segment of the power semiconductor market.

A major driving force spearheading the development of HV-HF power devices is the ongoing DARPA WBST HPE program focused on developing the technology deemed necessary to enable a Solid State Power Substations (SSPS) for future Navy warships. Current distribution approaches being considered for the next generation of aircraft carriers and destroyers employ a 13.8 kV AC power distribution that is stepped down to 450 V AC by using large (6 ton and 10 m^3) 2.7 MVA transformers. Substantial benefits in power quality enhancement, advanced functionality, size, and weight are anticipated by replacing this transformer with an all solid state design.

Figure 2 shows an example three level [2] solid state transformer indicating various secondary output options (EPRI reports 1001698). The transformer consists of, from left to right, a high voltage active front end (AFE) rectifier stage, a three level dc link, a high voltage inverter, a high frequency high voltage transformer, low voltage rectifiers, and various output modules such as a DC/DC converter, 400 Hz AC inverter, and various voltage level 60 Hz AC inverter outputs. The AFE rectifier stage provides a flexible utility interface with power factor correction. The high voltage inverter provides high frequency AC required to reduce transformer size and provides power quality voltage regulation functions. Both the AFE rectifier and high voltage inverter require HV-HF semiconductors; for example a single phase 13.8 kV, 15 kVA residential distribution transformer with 8 kV line to neutral requires semiconductors devices to switch at 15 kV, 3 A and the three phase 2.7 MVA SSPS requires devices to switch at 15 kV, 160 A.

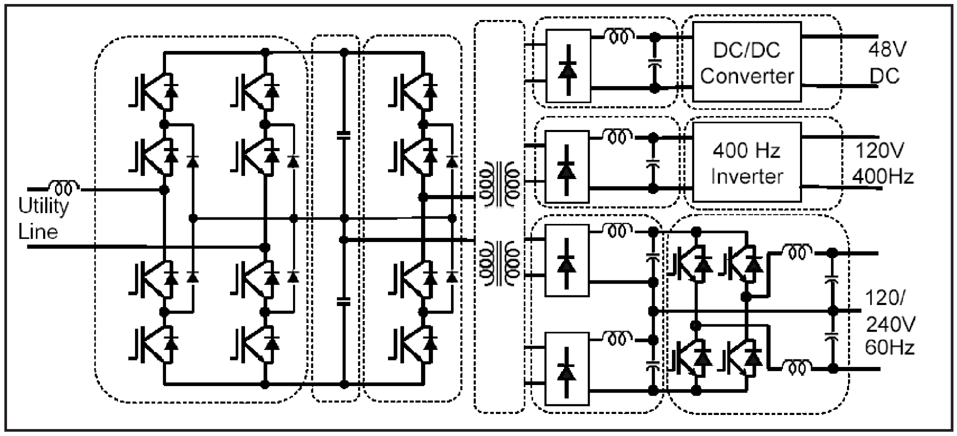

Figure 2. Example three level solid state transformer indicating various secondary output options.

RECENT PROGRESS IN HV-HF POWER DEVICES

Table 1 compares the basic material properties of Si and SiC. The wider bandgap of 4H-SiC results in higher operating temperature capability and better tolerance to heating during fault conditions. The primarily advantage of 4H-SiC for power devices is that it has an order of magnitude higher breakdown electric field. For a given blocking voltage requirement, the higher breakdown electric field allows the design of SiC power devices with thinner (0.1 times that of Silicon devices) and more highly doped (more than 10 times higher) voltage-blocking layers. For majority carrier power devices, such as power Schottky diodes or MOSFETs, the combination of 0.1 times the blocking layer thickness with 10 times the doping concentration can result in a factor of 100 advantage in on-resistance. For conductivity modulated devices such as PiN diodes or IGBTs, SiC results in a factor of 100 faster switching speed due to the lower lifetime required to conductivity modulate the thinner blocking layer.

Because the SiC material provides a much lower on-resistance than Silicon, conductivity modulated Silicon devices can also be replaced by majority carrier SiC devices with faster switching speed [3]. For example, new SiC Schottky diode commercial products have recently been introduced [4,5] to replace slower conductivity modulated Silicon PiN diodes. Although these first SiC power device product offerings have been low voltage (300 V to 1200 V) Schottky diodes, the HV-HF devices discussed below break the Silicon voltage capability limit and will be a key enabling technology of the future.

MATERIAL PROPERTIES	SILICON	4H-SIC
Bandgap (eV)	1.12	3.2
Breakdown Field (MV/cm)	0.3	3.5
Thermal Conductivity (W-cm/K)	1.5	4.9
Electron Mobility (cm^2/V-sec)	1500	1000

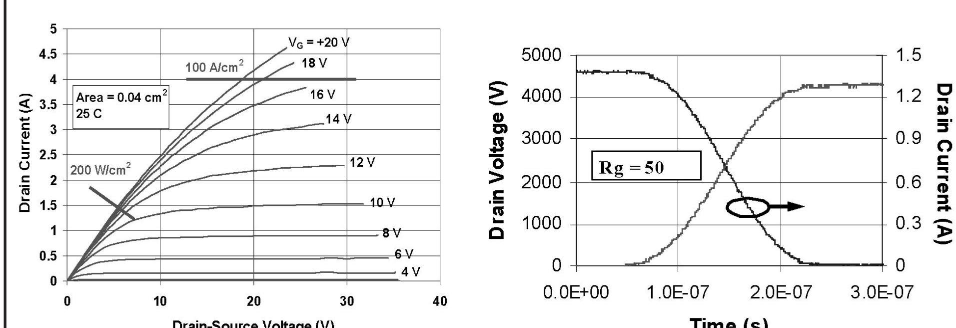

Figure 3. SiC 10 kV power MOSFET: (a) current voltage characteristics and (b) switching waveforms.

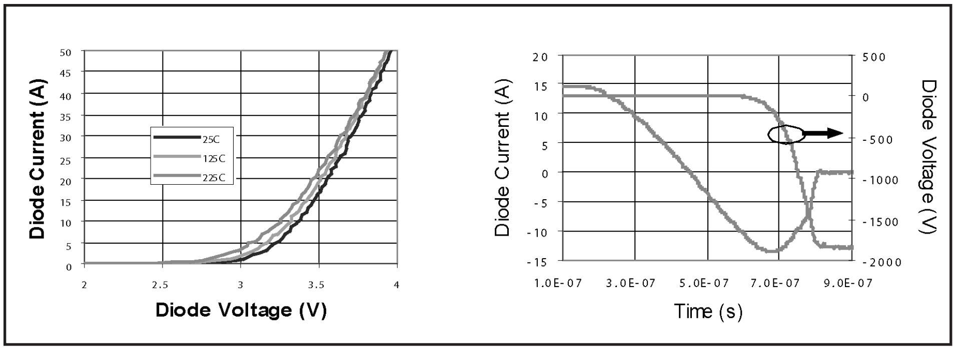

Figure 4. SiC 10 kV PiN diode: (a) current votlage characteristics and (b) reverse recovery characteristics.

Figure 3a shows the output current voltage characteristics of a 0.04 cm2 10 kV 4H-SiC power MOSFET [6]. The continuous current capability of 1.5 A indicated on the figure is determined using the 200 W/cm2 power dissipation capability of typical power device packages. The 4.6 kV bus, 1.3 A switching waveforms for this device shown in Figure 3b indicate a 100 ns switching time for the gate resistance of 50 Ohm resulting in a 0.3 A peak gate current. The measured turn-on and turn-off switching energy for this conditions is approximately 0.15mJ resulting in a switching power loss of 112 W/cm2 at 15 kHz. The static power loss for 50% duty cycle and the 1.3 A is approximately 75 W/cm2. Thus this device can operate with a 4.6 kV bus, 50% duty cycle, and 15 kHz in a typical 200 W/cm2 power package. The on-state voltage and switching parameters indicate that the devices are well matched for paralleling or large area die.

Figure 4a shows the forward conduction characteristics at different temperatures for a 0.5 cm2, 10 kV SiC PiN diode indicating a continuous current rating of approximately 30 A (60 A/cm2) [7]. The SiC PiN diode forward conduction characteristics only have slight temperature dependence where the current increases with temperature in the lower current range and decreases with temperature in the high current range. Thus the device should share current well when paralleled in a high current module. Reverse recovery characteristics for the 10 kV, 0.5 cm2 SiC PiN diode are shown in Fig. 4b. The reverse recovery time is 200 ns. This 10 kV SiC diode has a better on-state voltage to reverse-recovery time tradeoff than commercial Si 5 kV diodes and there are no Si diodes with 10 kV blocking capability. Thus, these devices represent a revolution in rectifier performance and capability for high voltage, high frequency power conversion applications.

CONCLUSIONS

The emergence of HV-HF devices is expected to revolutionize utility and military power distribution and conversion by extending the use of PWM technology to high voltage applications. SiC power MOSFETs with 10 kV, 1.5 A, 15 kHz switching capability and PiN diodes with 10 kV, 30 A, 200 ns reverse recovery time have already been demonstrated. The DARPA WBST HPE program is expected to develop half -bridge modules with 110 A, 15 kV, 20 kHz capability in the next few years. The emergence of HV-HF power devices presents unique opportunities and challenges to the power electronics industry in specifying the device requirements and establishing PWM converter topologies for high voltage applications.

ACKNOWLEDGEMENTS

Contribution of the National Institute of Standards and Technology; not subject to copyright. The device results presented here were developed by Cree Inc. with support from Dr. John Zolper at DARPA under ONR contract N00014-02-C-0302 monitored by Dr. Harry Dietrich.

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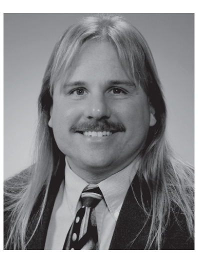

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