Transformational Opportunities for High Power Electronics

John C. Zolper
DARPA/MTO, Arlington VA
1-703-696-7039 / jzolper@darpa.mil

Abstract

In this paper, we describe the current progress, and future system level impact, of high power electronics based on silicon carbide. DARPA/MTO's current High Power Electronics program is highlighted.

1. INTRODUCTION

The move to more electric platforms has been touted by all the services as the path for revolutionizing platform capabilities. The interest in going to electric drive and weapons is driven by the potential to enable more agile and more capable platforms that enhance force projection. To allow this vision to be realized, it is becoming apparent that the core power distribution and control architecture must be also modernized. This talk will discuss the potential role a new class of power electronics components, based on the wide bandgap semiconductor silicon carbide, is expected to play in enabling these future platforms.

2. More Electric Platforms

All four services are exploring increased use of electric motors and actuators throughout their next generation of platforms. The impetus for using direct electric motor drive is the increased capability achieved by eliminating the gear box and employing electronic control to determine the motors torque. Electric motors can supply a wider range of torque than conventional all mechanical machines. However, to realize the full advantage of electric drive, especially on large platforms such as a Navy carrier or destroyer, advances are also needed in the controlling power electronics. For example, in a Naval carrier with power bus distribution at 13.8 kV, conventional conversion topologies employ step down transformers that dominate the size of the conversion electronics. For instance, a 2.8 MVA transformer for stepping down from 13.8 kV to 440 V can be 6 tons and 10 cubic meters. This large size forces the power distribution system to be designed around the conversion transformers, rather than the power system being designed around a mission need, since the transformer location largely determines the power system architecture. However, if a solid state power substation (SSPS) can be realized whereby high performance semiconductor switches and diodes are used to condition the power line, the size of the transformer can be markedly reduced and the power conditioning can be configured closer the point of use. Such a distributed power architecture will be more flexible and hence more survivable.

Another attractive attribute of electric platforms is that when the power is not being used for propulsion, it can be redirected to other electronic applications. This is not the case for conventional direct drive platforms that can only use the propulsion turbine power to drive the primary propulser. The vision for future Naval ships is to use excess available electric power for electromagnetic weapons, high power lasers, or electromagnetic aircraft launch systems. This can only be realized, however, if the electronic power distribution systems can rapidly redirect and recondition the electric power to the desired load in real time.

3. Silicon Carbide Power Electronics

SiC has the unique combination of a high critical electric field, good carrier mobility, and high thermal conductivity that enables high performance power switches and diodes to be realized. In addition, a thermal oxide can be grown on SiC, similar to that of Si, to yield inversion mode devices. Inversion mode MOSFETS have the desirable normally off characteristic preferred for power devices. Further, since SiC is an indirect bandgap semiconductor, again in analogy to Si, it has an acceptably high minority carrier lifetime to support conductivity modulation in bipolar devices to produce low on-state resistance in high voltage components. All of these attributes combine to make SiC an attractive candidate for high duty cycle, high efficiency power circuits for future DoD applications.

The utility of SiC can be seen in Figure 1 that shows a representative switching waveform for a Si diode versus a SiC diode in a 600 V half bridge circuit. Because the SiC diode can be a unipolar Schottky device versus the minority carrier PIN diode required in Si (Si must employ a PIN to attain acceptable low reverse leakage and on-state voltage), the SiC diode has 7 times less reverse recovery charge than the Si PIN diode. This translates to less loss in the power circuit and allows high frequency switching of the circuit.

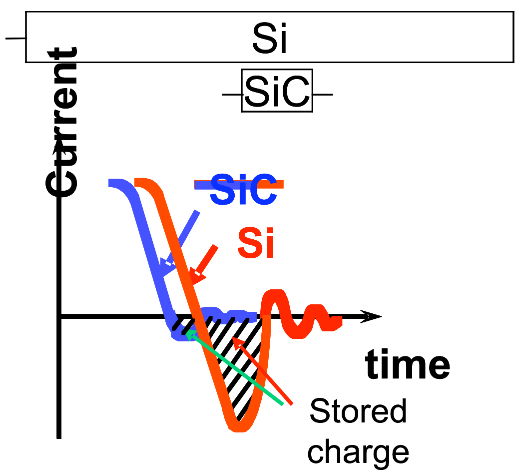

Figure 1: Representative device thickness and reverse recovery curves for a Si PIN diode and a SiC Schottky diode in a 600 V half bridge. The more rapid return to zero current for the SiC diode demonstrates less stored charge, and hence less circuit loss, as well as faster switching capability.

Since passive components such as inductors and capacitors scale in volume roughly as one over the square root of the switching frequency, the higher duty cycle afforded by SiC compared to Si will have a dramatic effect in reducing the size and weight of a power distribution and conversion system. In one example, when comparing a conventional 60 Hz 2.7 MVA transformer-based down converter versus a 20 kHz SiC-based solid state power substation (SSPS), close to a factor of 2 reduction in the converter size and weight has been projected.[i] Furthermore, a solid state power substation will have an enhanced power quality factor, digital control and reconfigurability, and superior control of power sag, flicker, and harmonics.

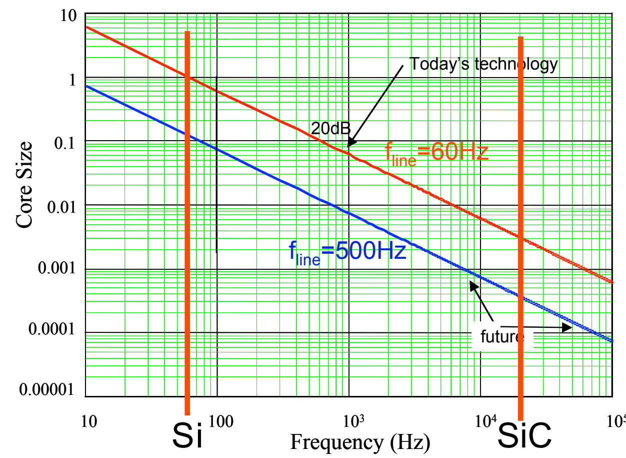

Figure 2: Relative transformer core size dependence on frequency. The increase switching frequency of SiC power electronics will enable a 100 fold reduction in the size of the transformer core.

4. DARPA's High Power Electronics Program

To realize a robust SiC power electronics technology, DARPA/MTO initiated a High Power Electronics program in 2002. The initial focus of the effort was to establish the core materials capability to include low defect density 4H n-type SiC wafers and high purity thick (100 to 150 micron) device quality epitaxy. This thick epitaxy is required for producing devices with a blocking voltage ≥ 10 kV.

The objective of the HPE program is to enable large area (≥1 cm^2) SiC devices to be realized with acceptable yield. To this end, an initial program milestone was established to demonstration total catastrophic defects (i.e. defects that have been shown to cause complete device failure, usual embodied as an electrical short) of ≤ 1.5 defects/cm^2 with a program goal to further reduce this to ≤ 0.5 defects/cm^2. As shown in Figure 3, achieving these defects levels in the starting materials (substrate plus epitaxy) will support a 1 cm^2 device yield, limited only by the defects, of 25% at 1.5 defects/cm^2 and >50% at 0.5 defects/cm^2.

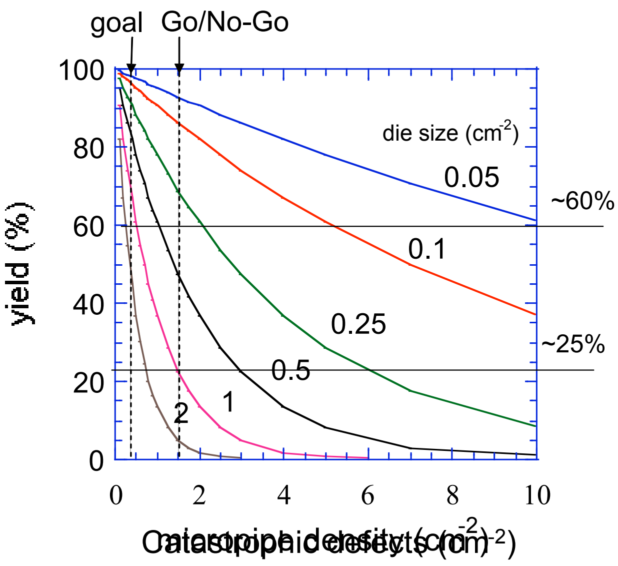

Figure 3: Projected device yield versus catastrophic defect density assuming a uniform distribution of defects. The lines are for varying device areas or die sizes.

Currently the combined defect density for the starting substrate and from a 100 micron thick epitaxial layer have been demonstrated to be less than 1.5 defects/cm^2. Figure 4 shows the best result to date for a 75 mm 4H n-type SiC wafer with only 10 total micropipes (the known catastrophic defect) that represents a defect density of 0.22 defects/cm^2. While this is a "hero" result, typical wafers grown under the HPE program now regularly have micropipes densities less than 5 cm^{-2} with approximately 20% of the wafers grown having micropipe densities of 1 cm^{-2} or less.[ii]

100 micron epitaxial lightly doped blocking layers were also characterized for defects that cause diode failures. It was found, that some micropipes from the substrate dissociate during epitaxial growth and are not longer catastrophic to device operation. Other defects (e.g. carrot defects) where found to form during epitaxial growth, however. By optimizing the growth conditions and reactor configuration, a total defects density after 100 microns of epitaxy was demonstrated at 1.49 defects/cm^2. Further work is ongoing to increase the growth rate and further optimize the growth process.

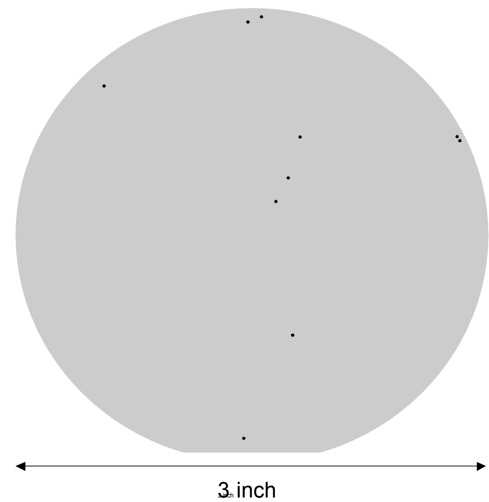

Figure 4: 75 mm (3 inch) 4H n-type SiC wafer with 10 total micropipes for a defect density of 0.22 cm^{-2}.

With the progress in SiC materials, the HPE program will be shifting its focus to the realization of high total power switches and diodes. The focus will be on devices for high voltage (≥ 10 kV) applications such as a 13.8 kV solid state power substation.

CONCLUSION:

SiC power electronics is posed to have a critical impact on future DoD more electric platforms. The increased switching frequency and reduced component loss will allow reduction in the size of power conversion and distribution systems. In addition, the implementation of advanced solid state power technology will enable new power systems architectures that will be more responsive to changing load requirements in a dynamic battle environment.

The present challenges to realizing a SiC-based power system lie in transitioning the recent research progress into a robust industrial technology base for high power components. This will be the thrust of the ongoing DARPA High Power Electronics program.

REFERENCES:

---

[i] A. Huang, "Solid State Power Substation," 10 kV Applications Workshop, Hilton Head Island, September 11, 2003.

[ii] H. Hobgood, “SiC Crystal and Substrate Technology: A survey of recent advances,” International Conference on Silicon Carbide and Related Materials, October 2003.