Commercially Available Cree Silicon Carbide Power Devices: Historical Success of JBS Diodes and Future Power Switch Prospects

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Abstract

Silicon Carbide has begun to fulfill its promise of delivering next generation power devices to the power electronics market. The SiC JBS diode has witnessed explosive growth recently thanks to the demand for higher efficiency systems. While accumulating over 150 billion field hours, the SiC JBS failure rate has remained an order of magnitude below the competing Si PiN diode products. After decades of research, Cree has finally released the first commercial SiC MOSFET which has overcome traditional gate oxide issues. The combination of SiC MOSFETs and SiC JBS diodes allows system designers to provide the highest efficiency systems to the marketplace. Despite the great potential for GaN power devices, careful examination of material and device qualification standards indicates that SiC power devices should remain attractive for 600 V and higher applications.

INTRODUCTION

Silicon Carbide (SiC) has become the material of choice for next generation power semiconductor devices to supplant existing silicon (Si) technology. The wider bandgap, higher thermal conductivity, and larger critical electric field allow SiC devices to operate at higher temperatures, higher current density, and higher blocking voltages than Si power devices. From an application standpoint, these advantages translate into SiC devices that allow the high speed majority carrier devices (Schottky diodes and MOSFETs) to be used at much higher voltage levels where typically Si minority carrier devices (PiN diodes and IGBTs) currently exist. Hence, system designers have the luxury of reducing conduction and switching losses by incorporating SiC power devices to produce higher efficiency systems. From a manufacturing standpoint, SiC has become a mature material system that is approaching defect-free quality with ever increasing wafer diameters currently demonstrated at 150 mm [1]. This combination of performance and manufacturability has resulted in the successful commercial adoption of SiC junction barrier Schottky (JBS) diodes and the recent commercial release of Cree's first power switch product—Z-FET™—the 1200 V, 80 mΩ SiC MOSFET, the first commercially available device of its kind.

JUNCTION BARRIER SCHOTTKY DIODES

The Cree SiC JBS diode is a relatively simple device that combines the conduction benefits of a Schottky diode and the blocking benefits of a pn junction. The key to its 600 V and 1200 V market acceptance has been the elimination of reverse recovery current resulting in higher efficiency switch-mode power supplies, AC motor drives and solar inverters. Since its introduction in 2004, the Cree Zero-Recovery™ JBS diode has accumulated over 150 billion hours in the field with a failure rate of less than 0.5 failures per billion device hours which is an order of magnitude lower than competing Si PiN diodes. In addition to improving reliability, the cost has also been reduced. R&D innovations have resulted in smaller chip sizes and larger defect free material while manufacturing experience has reduced fabrication induced defects and lowered the cycle time. The end result is a 60% reduction in the ASP since product introduction thereby dramatically accelerating growth to achieve a CAGR of 68%. In FY2010, Cree maintained its leadership in the high-efficiency power electronics market by shipping over 70 billion Volt-Amperes of SiC JBS diodes (Fig. 1) while introducing the latest generation of Z-Rec™ devices that include 1700 V diodes.

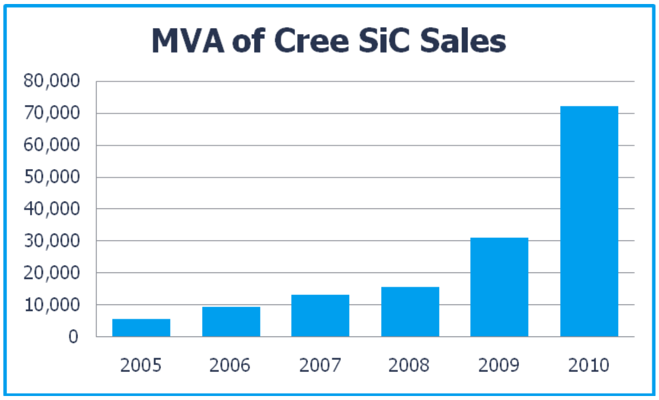

Fig. 1. Explosive growth of Cree SiC sales resulting in over 70 Giga-Volt-Amperes of power devices sold in FY2010.

MOSFETs

The SiC JBS diode provides an interim solution for system designers where the turn-on losses of the Si IGBT are significantly reduced. Ultimately, the turn-off losses of the switch can also be reduced by replacing the Si IGBT with a Cree Z-FET™—the first commercially released SiC MOSFET for high volume manufacturing. Comparing total losses of the 1200V SiC MOSFET against a commercially available 1200 V Si IGBT, the SiC MOSFET outperforms the Si IGBT in both conduction and switching losses resulting in an 80% reduction in power losses at 10 kHz or facilitating a 10x increase in the operating frequency at a 60 W power loss (Fig. 2). With the commercial release of the Cree Z-FET™, system designers finally have the opportunity to investigate potential ultra high efficiency systems based on all-SiC power device components.

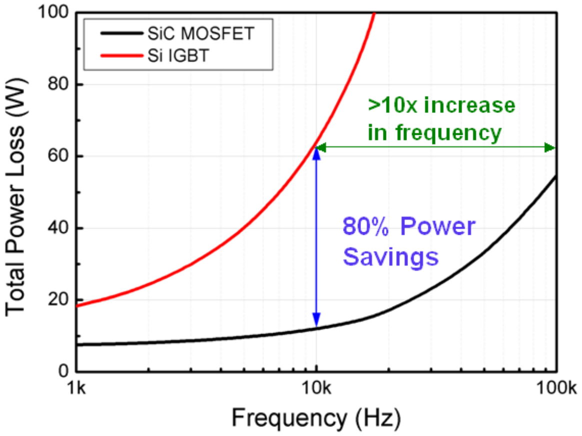

Fig. 2. Total power loss vs. operating frequency plot showing the marked advantage of 1200 V Cree Z-FET™ over existing Si IGBTs.

In the course of developing the Cree Z-FET™, considerable resources have been invested in overcoming traditional SiC MOSFET issues like the quality of the MOS interface, the reliability of the gate oxide, and the stability of the device electrical properties. Nitridation annealing of the SiC MOS interface has been shown to effectively raise the electron channel mobility to modest values [2]. Although further improvements are being investigated in R&D, the quality of the current MOS interface has enabled SiC MOSFETs with 75% reduction in the conduction losses over a Si MOSFET and a 55% reduction over a Si IGBT. Nitridation, coupled with careful device design, has also improved the gate oxide reliability. Dielectric strength measurements confirm a uniform distribution centered around 10 MV/cm consistent with theoretical values predicted for the SiO_2 gate dielectric. Time-dependent-dielectric-breakdown (TDDB) measurements performed on small area MOSFETs (identical cellular structure as the Z-FET with ~10,000x fewer cells and no termination for high voltage) predict SiC gate oxide lifetime to be sufficiently long at device operating conditions and comparable to, if not better than, Si MOSFET TDDB [3] at 175°C (Fig. 3). The improved SiC gate oxide lifetimes have been independently confirmed by Dr. John Suehle at NIST and Dr. Robert Kaplar at Sandia National Laboratory.

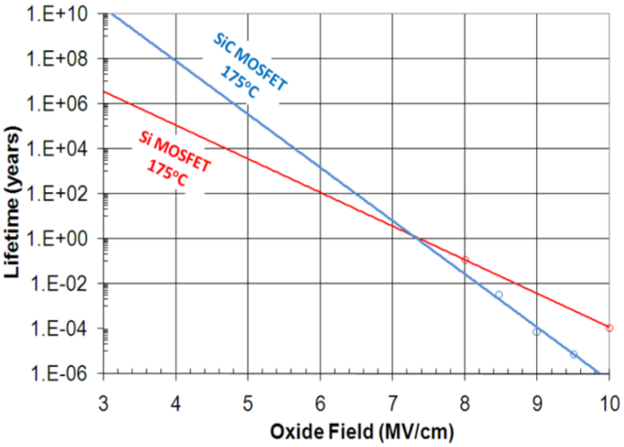

Fig. 3. Gate oxide lifetime extrapolated from high field TDDB measurements predicting adequately long lifetime for the SiC MOSFET at 175°C.

The other half of gate oxide reliability is the stability of the gate electrical properties. SiC MOSFETs, like its Si counterpart, have an inherent amount of threshold voltage (V_T) shift ~0.2 V due to border traps [4]. The careful design of post-oxidation processing steps to minimize any subsequent oxide trap generation has resulted in V_T shift of ~1 V after HTGB stressing (Fig. 4). Although this may appear to be a concern, it should be noted that the HTGB is a constant gate bias applied at 150°C for 1000 hr which results in significant electron trapping. In the field, the MOSFET will actually be switched on and off thereby receiving gate biases of 20 V on and 0 V off. The off-state relaxes the oxide field thereby allowing the trapped electrons to emit. To properly gauge field stability, the SiC MOSFET has been subject to a new gate stress—high temperature gate switching (HTGS)—where the gate voltage is switched between 20 V and 0 V at 20 kHz and 50% duty cycle to simulate a more realistic operating condition. In HTGS stressing, the SiC MOSFET has demonstrated excellent gate stability with very minimal changes in the relevant device properties, as shown in Fig. 5.

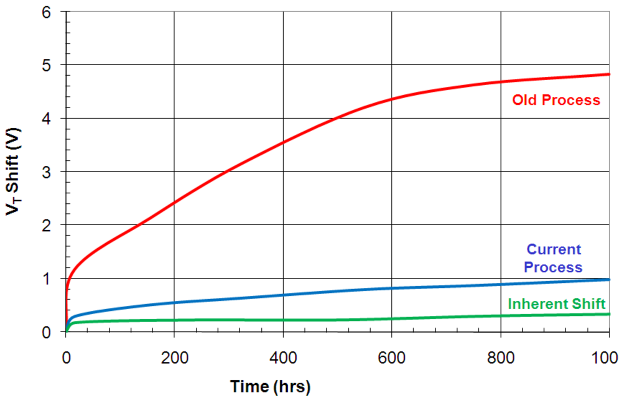

Fig. 4. Optimized processing reduces V_T shift from 5 V to 1 V during HTGB stressing.

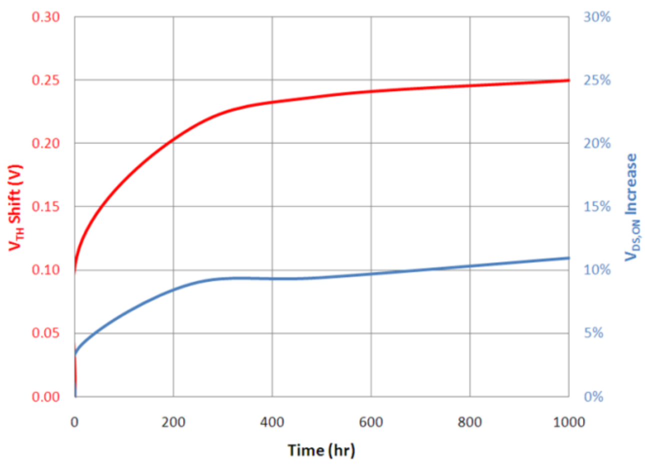

Fig. 5. HTGS stressing shows a 0.25 V increase in V_T resulting in only a 10% increase in $V_{DS,ON}$.

COMMERCIALIZING WIDE BANDGAP POWER DEVICES

In the evolution of SiC power devices from invention to commercial release, several high voltage derating steps occur. At invention, the device is typically specified by its avalanche breakdown voltage which was 1700 V for the SiC MOSFET. After the successful fabrication of several thousand MOSFETs, an avalanche breakdown distribution demonstrates that the MOSFET design generated a family of parts ranging from 1400 V to 1900 V which effectively derates the device to 1400 V. A final 200 V derating occurs to make the novel device technology robust enough to pass stringent JEDEC/AEC qualification standards. Hence, for commercial purposes, the SiC MOSFET is rated for 1200 V even though it has a 1700 V median avalanche breakdown (30% derating). The amount of derating naturally reduces as the device technology matures from the accumulation of both manufacturing and field data. It is expected that power devices fabricated on competing wide bandgap materials like Gallium Nitride (GaN) will have additional derating due to the orders of magnitude higher defect densities and the high surface fields associated with a lateral device structure. For example, GaNPowIR™ 600 V devices on high defect density GaN-on-Si epitaxy have been demonstrated to have an on-resistance that predicts 4 kV breakdown from the ideal GaN material properties (85% derating as shown in Fig. 6) [5]. This indicates that GaN power devices may ultimately be a viable solution for applications below 600 V where they provide a substantial advantage over Si devices. SiC power devices should remain the attractive choice at the higher voltage levels.

CONCLUSIONS

While SiC JBS diodes have flourished in the field with steady growth and industry leading field reliability statistics, the SiC MOSFET power switch device has been successfully developed into a commercially released product by overcoming historical issues with the gate dielectric. The availability of SiC power switches and rectifiers will usher a new generation of compact, ultra high efficient systems to meet the ever increasing demands for energy efficiency.

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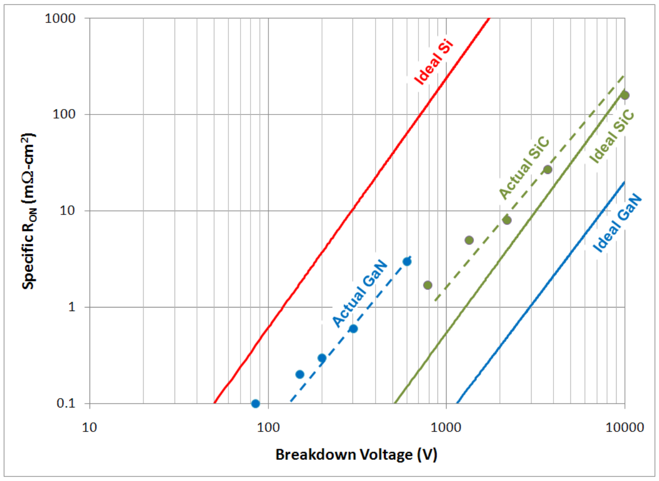

Fig. 6. Comparison of actual SiC MOSFET (Cree and Rohm [6]) and GaN power switch (IR [5]) performance against their ideal values. The more technologically mature SiC power switch technology shows only a small amount of derating (difference between Actual and Ideal lines) while the novel GaN power switches suffer from a large derating factor due to material defects and design issues.

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ACRONYMS

AC: Alternating Current
AEC: Automotive Electronics Council
ASP: Average Selling Price
CAGR: Compound Annual Growth Rate
FY2010: Fiscal Year 2010
HTGB: High Temperature Gate Bias
IGBT: Insulated Gate Bipolar Transistor
IR: International Rectifier
JEDEC: Joint Electron Device Engineering Council
MOSFET: Metal Oxide Semiconductor Field Effect Transistor
NIST: National Institute of Standards & Technology
SiO_2: Silicon Dioxide