DEVELOPMENTS IN HYBRID SI – SIC POWER MODULES

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Abstract
This paper investigates utilization of silicon carbide (SiC) Schottky power diodes as inverter Free Wheel Diodes (FWD) in a commercially available standard Econopak module also packaged with latest generation low-loss IGBT silicon. Static and switching characteristics of SiC diodes over standard module operating temperature 25°C to 125°C (298 K - 398 K) are measured. Module Turn-on, Turn-off and conduction losses vs. frequency are calculated and measured for three phase motor drive operation. Measurements are compared to standard modules using all Silicon (Si) IGBT- diode. System benefits justifying the increased SiC diode cost, such as EMI reduction, increased efficiency, reduced magnetic filter volume and reduced cooling requirements at higher allowable switching frequencies is investigated.

Introduction
Fast and soft recovery current aspects of Si FWDs have been a design issue in Voltage Source Inverters (VSIs) since its inception in 1960 and a recurring nemesis to advancing power electronics. The high peak recovery current characteristics of Si diodes lead to increased voltage stress and poor device utilization for the IGBT switch, and also increases diode loss due to design trade-offs of higher forward voltage drop for lower recovery current. While, IGBT advancement has continued with $V_{ce(sat)}$ drops approaching theoretical limits and Turn-on/ Turn-off switching times approaching a lossless switch, the present Si diode reverse recovery loss restricts further Turn-on loss reduction. Fast switching speed and slightly higher voltage drop features of available SiC Schottky diodes can greatly reduce total power loss and component stress as compared to Si PiN diodes [1]. Features of SiC freewheel diodes are [2]:

- Zero diode reverse recovery loss independent of collector current IC and TJ
- Reduces total inverter module losses
- Reduces pole deadtime & deadtime compensation for lower current distortion

Benefits of developing Hybrid IGBT–SiC FWD modules for application in VSI topology are:

- Size and weight reduction - High frequency operation capability
- High efficiency and low loss - High reliability at high temperature
- Cooling requirement reduction - Magnetic filter size reduction due to high frequency

However, the desirable SiC diode features had low market acceptance in 1999 due to a high per unit cost increase over silicon [3]. SiC diode usage in low voltage IGBT switch mode supplies was first investigated in 2003 [4]. In 2003, a 600V SiC JFET switch & 600V SiC Schottky diode in a three phase motor drive was first demonstrated [3]. While 1200V SiC JFET switches may be years away, 1200V 25A SiC diodes are available today [5,6]. This paper discusses recent developments in hybrid power modules using existing 1200V Silicon IGBT – SiC diode for motor drives. A hybrid approach is a useful first step to both power electronic industries and SiC diode manufacturers, who need a market base to further refine material optimization and reduce fabrication costs. Following is technical advantages and technical obstacles to packaging/manufacturing 1200V 25A SiC diodes with Si IGBTs.
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**Parts Characterized: All Si vs. Hybrid Si – SiC Diode**

Fig. 1 shows a 3-phase module consisting of Si IGBT - Si diode or Si IGBT - SiC diode. Eupec has lowered silicon IGBT $V_{ce(sat)}$ by 5% from 2.45V to 2.0V with “KE3” (2002) and to 1.9V with “KT3” (2003) designs and is approaching a theoretical IGBT VCE limit. Thus, a paradigm shift to SiC JFET switch may be forthcoming. Diode energy loss increased 12% from 2001 to 2003 modules, but overall switch loss decreased showing design tradeoff in recovery loss vs. IGBT Turn-on loss. The faster KT3 switch has a 6% lower (energy-loss/amp) vs. KE3. Hot (125°C) and cold (25°C) characterization of all Si (25A IGBT & diode) parts were compared to FP25R12KT3 & FP25R12KE3 modules with a 12A SiC diode. Fuji “S Series” IGBT 1200V-25A 7MBR25SA120 had 25A Rockwell Scientific (RSC) SiC Schottky diodes for comparison.

**Physical Size Reduction: Silicon Si PiN vs. SiC Diode**

Fig. 2 shows SiC reduced die size has less area for bond wire attach. Reduced thermal heat transfer surface area is partially offset by thinner SiC wafer and higher thermal conductivity. SiC diodes may run at higher temperatures than Si, but solder melting and bond wire thermal cycling fatique may limit ratings until new bonding technologies are developed. For equal device amp and voltage rating, the SiC parts occupy 30% less area than Si PiN diodes.
Physical Size Reduction: Silicon Si PiN vs. SiC Diode

Fig. 3 shows Si Pin VF decreases at 125°C whereas SiC VF at 125°C increases 1.5x compared to 25°C value. Reduction of SiC 125°C forward resistance slope requires further research in material physics and termination contacts. SiC higher conduction losses are mostly offset by zero recovery loss. Optimum SiC usage depends on thermal package limitations. The SiC diode chips characterized showed multiple SiC diode chips were required to thermally handle applications under low power factor (high diode conduction time) and overload duty cycles (high current stress). Thus, initial reduction in surface area gained with SiC is partially nullified.

Device Characterization: Dynamic Test Fixture using Single Phase Pole

Fig. 1 inverter is also a device characterization fixture (dotted box) if Phase A inductor is reconnected to the (-) DC bus. Bottom IGBT is gated off and Top IGBT is double pulsed under controlled heatsink temperature, simulating inductive load operation. Pearson 2878 current CTs and P5100 Tektronix voltage probes were used. The 1st pulse Turn-on ramps load current to rated 25 Amp peak (Apk), followed by 1st Turn-off where the bottom FWD diode conducts. Next, 2nd Turn-on pulse picks up 25A load and Fig. 1 diode recovery current (I_Recovery) path to turn off the bottom diode. 2nd Turn-on pulse ramps Ic to 60 Apk, the 300% over-current trip value, where 2nd Turn-off occurs. The FP25R12KT3 device at 600 Vdc, recommended RGate = 36 W, and 1250C is the test condition used for all waveforms taken, unless otherwise specified.

All Silicon KT3 vs. KT3-SiC Characterization: Eoff, Eon, Eoff & Ringing Phenomenon

IGBT Turn-Off Energy (Eoff): IGBT Turn-off energy with SiC is ~3% lower Eoff than standard Silicon @ 60 Apk 2nd Turn-off and ~3% higher Eoff than standard Silicon at 25 Apk 1st Turn-off. Fig. 4 peak power is similar for Si & SiC diodes. Energy loss is calculated by integrating power vs. time profile. Conclusion is that SiC FWDS have no effect on IGBT Eoff.

IGBT Turn-On Energy (Eon): 2nd IGBT Turn-on waveforms of Fig 5 at 25 Apk load show the IGBT-Si diode has 18 Apk reverse recovery, whereas the IGBT-SiC diode has a 4 Amp peak capacitive charging current. The SiC diode reduces peak IGBT Turn-on power loss by 54% and reduces peak IGBT Eon by 60%. Conclusion is SiC FWDS has a large effect on IGBT Eon.

Diode Reverse Recovery Energy (Eoff): 2nd IGBT Turn-on waveforms at 20A (Turn-off diode) of Fig. 6 show IGBT-SiC diode reduces peak IGBT Turn-on peak IC to just load amps and reduces peak reverse recovery power to virtual “0” %. The IGBT-SiC diode also reduces reverse recovery time from 700 ns to 80 ns allowing high frequency operation without distortion. Conclusion is SiC FWD has a large effect on diode Eoff and total loss.
Ringing Phenomenon:
A gate ringing phenomenon with KT3-SiC, but not the S Series–SiC modules, occurred as $R_{\text{GATE}}$ was lowered to further reduce IGBT Turn-on loss, allowable since $I_{\text{RECOVERY}}$ is 0. Fig 7 (left) shows typical $V_{\text{GATE}}$ & $I_{\text{GATE}}$ ringing. Theory 1 explains gate ringing due to higher $V_{\text{CE}}$ $dv/dt$ at Turn-on, which now excites unforeseen module parasitic resonant frequencies. The all Si module had a $V_{\text{CE}}$ $dv/dt$ of 120V in 120 ns or 1.0 V/ns, whereas the SiC module is 50 % faster with 120V/ 80 ns or 1.5 V/ns. Theory 2 is that a reduced VCE – IC switching loss with SiC diodes reduces an effective circuit damping resistance. For standard $R_{\text{GATE}} = 36$ W, IGBT switching energy loss with SiC diodes is 59 % that of an all Si module. Fig. 7 compares Eupec KT3 with Infineon SiC diode against Fuji S Series with RSC SiC diode, both with reduced $R_{\text{GATE}} = 24$ W. The S Series with no ringing has slower $dv/dt$ (3 vs. 1.2 V/ns) and 50 % higher energy loss than KT3- SiC, supporting both theories.

Energy Loss Summary: Silicon PiN FWD vs. Schottky SiC
Fig.8 shows typical $E_{\text{on}} = 3.3$ mJ for rated IC & $R_{\text{GATE}}$ of the all silicon module. $E_{\text{on}}$ reduces by 37 % under same conditions but with the SiC diode. A dramatic 85 % $E_{\text{on}}$ reduction occurs if $R_{\text{GATE}}$ is further reduced to 8 W. $E_{\text{off}}$ does not change with either Si or SiC diodes under any $R_{\text{GATE}}$. Diode $E_{\text{on}}$ is reduced 94 % to virtual zero loss with SiC diodes regardless of $R_{\text{GATE}}$.

Three-Phase Watts Loss Summary:
All Standard Silicon vs. Hybrid - SiC Three phase watts loss @ 4 KHz switching is calculated using Eupec IPOSIM program. IGBT steady-state loss ($P_{\text{SS}}$) uses VCE- IC curve fit data. IGBT switching Loss ($P_{\text{SW}}$) ~ ($E_{\text{on}} + E_{\text{off}}$) * f.
Diode steady-state loss \( P_{\text{D}} \) uses \( V_F \) vs. \( I_F \) curve fit data. Diode switching loss \( P_{\text{RR}} \approx 0.125 \times E_{\text{rr}} \times f \). Power loss per phase = \( P_{\text{SS}} + P_{\text{SW}} + P_{\text{D}} + P_{\text{RR}} \). Calculated Watts per Switch, IGBT and diode loss of Fig. 1, is multiplied by 6 to obtain Fig. 9 total watt loss for Si and SiC modules switching at 4, 6, 8, 15 and 20 kHz. The all Si module switching at 20 kHz has 2.8x more losses than at 4 kHz. In contrast, a SiC module with reduced \( R_{\text{GATE}} \) increases only 1.5x (0.77 to 1.2 pu) from 4 kHz to 20 kHz. KT3-SiC at 4 kHz with standard and polarized (Turn-on = 18 \( \Omega \) / Turn-off = 36 \( \Omega \)) \( R_{\text{GATE}} \) show total module loss is 88% and 77% of the all Si Module, respectively. This is due to \( E_{\text{on}} \) loss \( \approx 0 \) and reduction of IGBT \( E_{\text{off}} \) loss in Fig. 8. Significant loss reduction is observed at 20 kHz with KT3-SiC being 58% and 41% of KT3-Si losses. The main point is KT3-SiC at 15 kHz dissipates the same 1 pu power and uses same heatsink as present KT3-Si modules switching at 4 kHz! Fig. 9 calculated results were within < 5% of measured using calorimeter methods.
SiC Diode System Benefit: Radiated & Conducted EMI Reduction

Fig. 11 Near Field probe measurements at the DC bus and output pins show an 8 db improvement with SiC diodes. A 3 meter Far Field antenna test shows 6 db SiC diode advantage @ 3 MHz & 16MHz due to absence of Si diode trr & tb risetimes of Fig. 6 and I_recovery path in Fig.1. SiC devices improve conducted emissions, but only at $\frac{1}{\pi \cdot T_b}$=16 MHz.
Conclusion

SiC area is ~ 30% that of Si die for equal ratings. SiC diode voltage drop is comparable to Si @ 25°C, but possibly 2x @ 125°C. SiC diodes have no effect on IGBT $E_{on}$ but reduce IGBT $E_{off}$ by 37%, peak IGBT turn-on power loss by 54% and peak IGBT peak device $I_{s}$ by 58% from $(I_{load} + I_{recovery})$ to $I_{load}$. SiC diodes have a large effect on reducing Err loss to virtual zero, independent of temperature or $I_{s}$ current and reducing reverse recovery time from 700 ns to 80 ns, reducing deadtime compensation and thus current waveform distortion. SiC diodes eliminate reverse recovery restrictions, allowing a lower $R_{gs}$ and even faster turn-on for reduced loss.

A lower $R_{gs}$ reduced IGBT $E_{on}$ by up to 85% but excited a turn-on oscillation problem due to possible faster $dv/dt$ and lower energy damping loss at turn-on attributed to $V_{ce-I_{s}}$ power loss.

Calculated loss summary at 4 kHz, showed all silicon modules replaced with SiC diodes reduced total module watts by 13%, while a lower $R_{gs}$ reduced total module watts by 24%.

The Hybrid KT3-Si calculated losses @ 15 kHz were comparable with 2005 Standard KT3 Silicon losses @ 4 kHz, implying a 3.75:1 improvement for the same heat sink cooling.

The Hybrid module with SiC diodes has other system benefits of -6 dB (2:1) to -10 dB (3:1) reductions in Near / Far field radiated emissions in the 3-24 MHz and -10 dB conducted emission reduction, but only near the 10 MHz and 22 MHz regions.

Acknowledgement:
The authors wish to thank E. Hanna of Rockwell Science Center & Eupec, Infineon, and Fuji Semiconductor for their participation, and Ken Phillips of Rockwell Drives and Dr. P. Chow of RPI for their support in writing this paper.

References


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Publication DRIVES-WP020A-EN-P – November 2006
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