Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp934-935

SiC Power MOSFETs and Diodes for Next Generation Power Modules

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1. Introduction

SiC power devices have matured to a point where the development of specific power modules for electric power conversion and distribution and is feasible. Using SiC power devices (MOSFETs and Diodes in 1.2 kV to 10 kV ratings) will reduce total losses (switching and conduction) by about 50% or more depending upon the breakdown voltage rating when compared to an equivalent Si IGBT/PiN diode solution, resulting in efficiency gains of several percentage points. In addition, SiC devices can safely work up to a junction temperature of 190ºC with conventional packages. The combination of reduced losses and higher temperature capability will reduce cooling requirements by as much as a factor of six.

2. Advantages of SiC Power Devices

The advantages of SiC power devices are well documented in the literature [1,2]: (a) Higher breakdown electric field, (b) High temperature operation and (c) higher thermal conductivity. The high breakdown electric field allows circuit designers to replace Si IGBTs and PiN diodes with SiC MOSFETs and Schottky diodes in 1.2 kV to 10 kV range. This virtually eliminates the reverse recovery charge in diodes and switches, resulting in a 60-70% reduction in switching losses in hard-switched applications at a bus voltage of 600 V. The percentage reduction in switching losses increases with higher bus voltages. Moreover, unlike silicon devices, the reverse recovery charge in the SiC MOSFETs and Schottky diodes does not increase with temperature. This means that the switching losses in SiC devices do not increase with increasing junction temperature. This is illustrated in Fig. 1, where the turn-off of a 600V Si PiN diode is compared with a SiC Junction Barrier Schottky (JBS) diode over temperature.

The second advantage of SiC devices is the ability to function reliably at high junction temperatures with low leakage current. SiC MOSFETs and Schottky diodes in high temperature packages have proved to be reliable at 200ºC and are capable of excursions to 300ºC for short durations. In contrast, Si IGBTs become unreliable above 150ºC and are generally restricted to a junction temperature of 125ºC. The standard packaging materials currently employed by the silicon industry are generally reliable up to 190°C. Therefore, if SiC MOSFETs and Schottky diodes are packaged in standard packages and rated up to a junction temperature of 190°C, the following argument can be made. Assuming a coolant temperature of 90°C and further

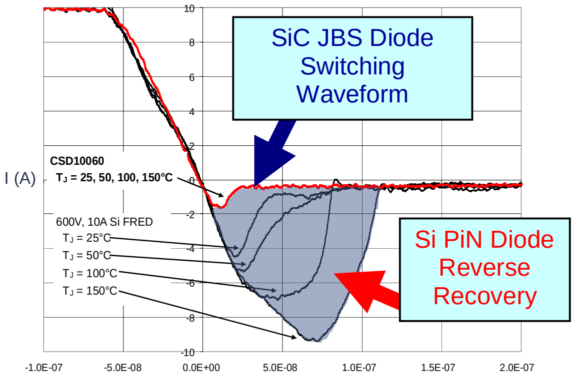

Figure 1: Comparison of a 600 V Si PiN diode and a SiC Junction Barrier Schottky (JBS) diode during turn-off.

assuming that the thermal impedance from junction to case is the same in all cases, we can conclude that the amount of heat flux which can be removed in the case of SiC is roughly three times that in the silicon case. Combining this capability with a 50% reduction in total losses in the case of SiC devices, one can conclude that the cooling requirements of SiC devices can be reduced by a factor of six in standard packages. This means that a designer can take advantage of the higher junction temperature of SiC devices and lower total losses in two ways: (1) Switch from liquid cooling to passive cooling resulting in significant savings in volume and weight (higher junction temperature, up to 190ºC), OR (2) Maintain the same cooling (junction temperature will be lower for SiC devices due to lower losses) and expand the survivability envelope of power electronics under conditions such as loss of coolants, or needing additional power for short duration.

3. SiC Power Modules

SiC power modules with ratings of 1.2kV/100A and 10kV/110A have already been demonstrated. The current development is focused on 1.2 kV/600 A power modules. Figs. 2 and 3 show the details of the 1.2 kV/100 A all-SiC power module developed under funding from the U.S. Air Force Research Laboratory (AFRL). The SiC MOSFETs in the module have a lower forward drop as compared to Si IGBTs up to 150ºC, as shown in Fig. 4.

The conduction and switching losses are compared between Si and SiC power modules at 20 kHz (Fig. 5). The all-SiC module shows a 30% reduction in total losses at room temperature and 54% reduction in total losses at 150ºC. This means that the SiC power module will run

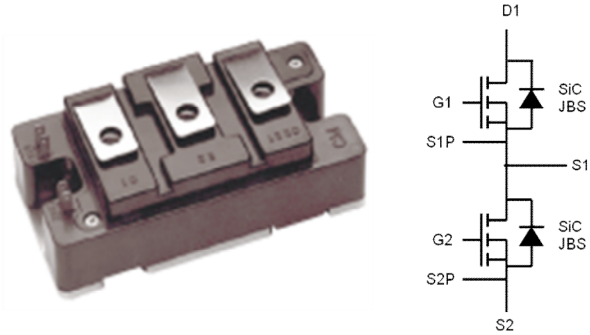

Figure 2: All SiC power module, rated at 1200 V/100 A, developed by Cree and Powerex.

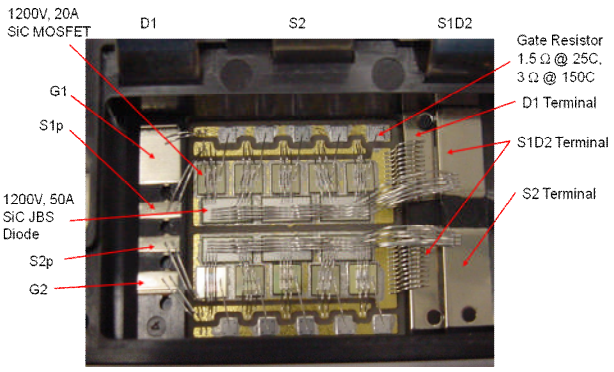

Figure 3: Internal details of the module shown in Fig. 2. It utilizes 1200 V/20 A SiC MOSFETs and 1200 V/50 A SiC Diodes.

much cooler and will have a 2-4% higher efficiency than a similarly rated Si IGBT module with similar cooling. Conversely, the SiC module can be run at the same junction temperature as the Si IGBTs with much reduced cooling.

The advantage of SiC MOSFETs and Schottky diodes become even better for higher voltage applications. For example, the conduction and switching losses of a 3.3 kV SiC MOSFET and Schottky diode are compared with a silicon IGBT and PiN diode in Fig. 6 at 1.5 kHz, which is the normal operating frequency of silicon parts. The total losses in the SiC MOSFET are only 100 W as compared to 375 W in the Si IGBT – a reduction of 73%. The losses in the SiC MOSFET operating at 20 kHz are still lower than Si IGBT operating at 1.5 kHz.

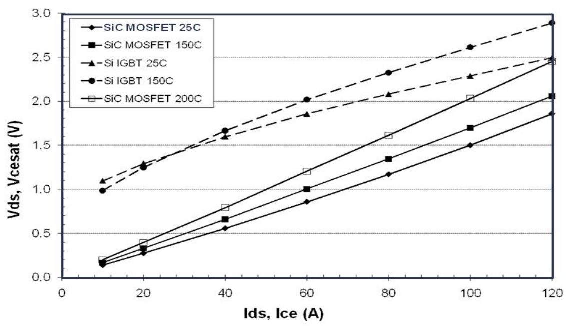

Figure 4: Forward drop across Si IGBT and SiC MOSFETs at 25ºC junction temperature vs total current.

Conduction Losses

	25 °C V-on	150 °C V-on	25 °C Pwr	150 °C Pwr
Si	2.29	2.62	114.5	131
SiC	1.36	1.63	68	81.5
% Reduction	40.61%	37.79%		

Switching Losses

	25 °C µJ	150 °C µJ	25 °C Pwr	150 °C Pwr
Si	12.6	18.2	252	364
SiC	9.5	7.3	190	146
% Reduction	24.60%	59.89%		

Total Losses

	25 °C Pwr	150 °C Pwr
Si	366.5	495
SiC	258	227.5
% Reduction	29.60%	54.04%

Figure 5: Comparison of conduction, switching and total losses in 1.2 V/100 A Si and SiC modules at junction temperatures of 25 and 150ºC.

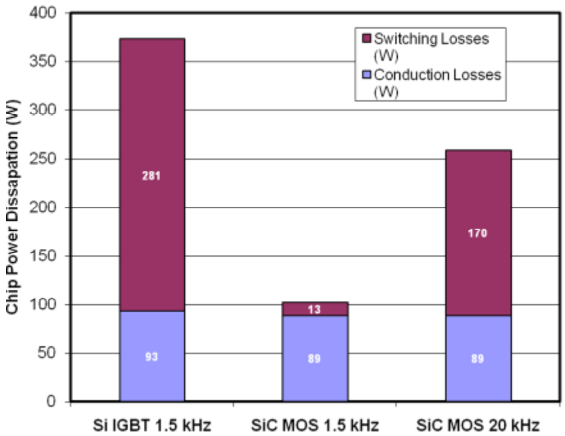

Figure 6: Comparison of switching and conduction losses for 3.3 kV SiC MOSFET and silicon IGBT

4. Conclusions

Rapid progress in SiC MOSFET and Schottky diode design in the 1 kV – 10 kV range has been achieved. These have been used in power modules to replace Si IGBTs and PiN diodes. There are two ways to take advantage of SiC components. One is to allow the devices to run hot and greatly reduce the cooling requirements for the system, and the other is to maximize efficiency and survivability under the same cooling conditions.

Acknowledgements

The support from the U.S. Air Force Research Laboratory (AFRL, Dayton, OH), the U.S. Army Research Laboratory (ARL, Adelphi, MD), the Office of Naval Research (ONR, Washington, DC) and DARPA (Washington, DC) is gratefully acknowledged. We also acknowledge the work of Scott Leslie and Powerex on the power module design and construction.

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