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ELECTRICAL AND THERMAL PERFORMANCE OF 1200 V, 100 A, 200°C, 4H-SiC MOSFET-BASED POWER SWITCH MODULES (PREPRINT)

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14. ABSTRACT
In this paper we report the electrical and thermal performance characteristics of 1200 V, 100 A, 200°C (T_j), SiC MOSFET power modules configured in a dual-switch topology. Each switch-diode pair was populated by 2 x 56 mm^2 SiC MOSFETs and 2 x 32 mm^2 SiC JBS diodes providing the 100 A rating at 200°C. Static and dynamic characterization, over rated temperature and power ranges, highlights the performance potential of this technology for highly efficient drive and power conversion applications. Electrical performance comparisons were also made between SiC power modules and equivalently rated and packaged IGBT modules. Even at a modest T_j=125°C, conduction and dynamic loss evaluation for 20kHz, I_d=100A operation demonstrated a significant efficiency advantage (38-43%) over the IGBT components. Initial reliability data also illustrates the potential for SiC technology to provide robust performance in harsh environments.

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Electrical and Thermal Performance of 1200 V, 100 A, 200°C 4H-SiC MOSFET-based Power Switch Modules

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Abstract. In this paper we report the electrical and thermal performance characteristics of 1200 V, 100 A, 200°C (T_j), SiC MOSFET power modules configured in a dual-switch topology. Each switch-diode pair was populated by 2 x 56 mm^2 SiC MOSFETs and 2 x 32 mm^2 SiC JBS diodes providing the 100 A rating at 200°C. Static and dynamic characterization, over rated temperature and power ranges, highlights the performance potential of this technology for highly efficient drive and power conversion applications. Electrical performance comparisons were also made between SiC power modules and equivalently rated and packaged IGBT modules. Even at a modest T_j=125°C, conduction and dynamic loss evaluation for 20kHz, I_d=100A operation demonstrated a significant efficiency advantage (38-43%) over the IGBT components. Initial reliability data also illustrates the potential for SiC technology to provide robust performance in harsh environments.

Introduction

Owing to the significant research and development efforts over the past 15 years, SiC materials and power device technology have rapidly matured. SiC substrates of 75 and 100 mm with low micropipe densities are standard products, and zero-micropipe wafers have been recently marketed [1]. Although dislocations, particles, and other performance detracting flaws remain and are the focus of ongoing improvement efforts, material quality is now primarily a yield and thus a device cost driver. These advances are reflected by demonstrations of a wide range of power devices with 300 V to multi-kV ratings and current capability of up to 75 A/die [2,3]. In addition, the legacy harsh-environment technology-pull for SiC and other wide bandgap semiconductors is rapidly being subordinated by renewed global interest in reduced energy consumption, hybrid vehicle commercialization, and alternative energy generation requirements for efficient, cost-effective power electronics. These factors have led to the pending emergence of SiC switching devices in the commercial market, long seen as a requisite compliment to existing SiC diode products prior to significant market penetration. Many applications will necessarily require device technology be provided as power modules (PM) designed to enable the accrual of SiC's potential. In this paper we report the performance characteristics of 1200 V, 100 A, 200°C, SiC MOSFET-based dual-switch power modules. Comparisons between SiC and low-loss insulated gate bipolar transistor (IGBT) PM's were also accomplished and are summarized in the following sections.

Module Design and Characterization

An evolutionary approach to the development of SiC MOSFET power modules was adopted in which Generation I modules utilized commercial polyphenyl sulfide (PPS) cases with 170 W/mK AlN substrates, 221°C liquidus 96.5Sn3.5Ag solder, and low CTE (~4 ppm/K) Cu-C baseplate components to satisfy intermediate 150°C heatsink temperature (T_{Sink}) requirements. This approach enabled rapid prototyping, units for environmental testing, and electrical performance comparison to commercial IGBT modules in identical form factor. Generation II modules, targeting a higher T_{Sink}=200°C capability, required custom design which incorporated high temperature materials, and an integrated heatsink enabling baseplate elimination. Gen I module substrates were fabricated in two configurations, Ia and Ib

using CREE, Inc. 4H-SiC MOSFETs and JBS diodes. Gen Ia utilized five 4.7 x 4.7 mm 20 A SiC MOSFETs and three 4 x 8.2 mm 50 A SiC JBS diodes for each of the two phase-leg switches and is shown in Fig 1a). Inductive impedance considerations, due to excessive wirebond length, and the larger die area required for current de-rating at 150°C or 200°C operating temperatures, necessitated the Ib

Figure 1. SiC module die layout for a) 20 A MOSFETs, b) 80 A MOSFETs, and c) die.

layout redesign and utilization of large area I_D=80 A, 56 mm^2 SiC MOSFETs. A populated large area die module is shown in Fig 1b in which two 80 A MOSFET and two 31.6 mm^2 JBS die per switch are used. Fig 1c) shows both the 20 A and 80 A MOSFET die for comparison. Fig 2 illustrates representative room-temperature I-V characteristics of both the 20 A and 80 A MOSFET die used in the Generation I modules, including typical specific on-resistivity values of 7.96 and 7.34 mΩ-cm^2 for V_{GS}=20V. Detailed design and terminal characteristics for these devices are published elsewhere [4,5]. Subsequent to packaging, individual switches in the dual configured modules were subjected to extensive static and dynamic electrical and thermal characterization. Fig's 3 and 4 illustrate representative post-fabrication yield screening data for several modules built using both 20 A and 80 A MOSFET, and 50 A JBS die. Fig.3 shows a typical four module switch average threshold voltage (V_{TH}) dependency on temperature using an I_D=10mA module definition at V_{TH}. The approximately 0.5 V difference between the 20 A and 80 A data in Fig 3 reflects the process dependency of V_{TH} and in this instance is due to slightly differing oxidation parameters used for the two lots of devices. On the other hand, the data shown is representative of the nominal V_{TH} observed. Fig. 4 shows the average measured switch forward voltage module (V_f) data for I_D=100 A. The figure includes curves for both 15 and 20 V MOSFET gate bias conditions as a function of temperature as well as the JBS diode-pair. As is typical of present SiC MOSFET device characteristics, the 20 V gate bias mitigates the T<100°C negative V_f coefficient for V_{GS}=15 V attributed to thermalization of the near bandedge interface state traps and the associated decrease in channel mobility and resistivity.

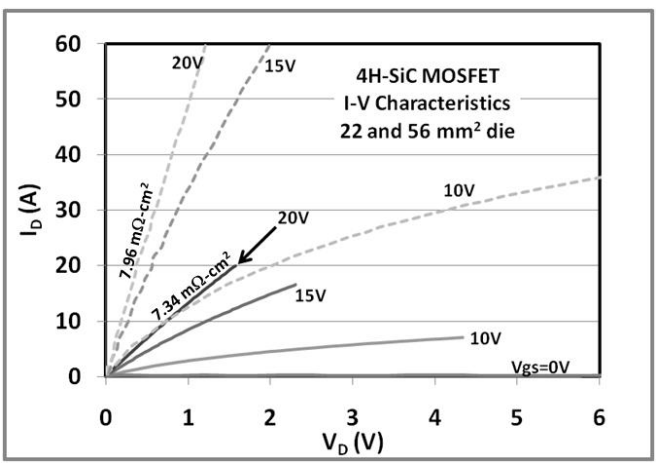

Figure 2. Typical I-V characteristics for 20A (solid lines) and 80A MOSFET's. $R_{ON,sp}$ shown for Vgs=20V.

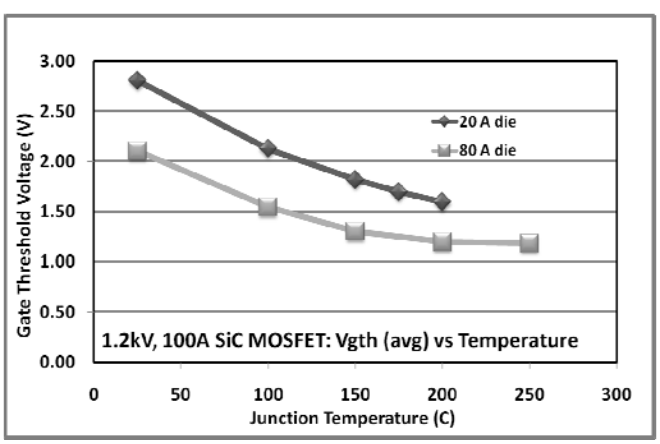

Figure 3. SiC power module V_{TH} data as a function of temperature. Data represents the average of 4 modules (5 parallel 20A or 2 parallel 80 A die).

Thermal Considerations. Development of modules designed for 150 – 200°C operation necessarily require consideration of thermal expansion coefficients (CTE), elastic moduli, bonding metallurgies, potting dielectric stability, and other factors related to thermal cycle-life and operational reliability over an expanded temperature range [6]. In addition to peak operational temperatures, consideration must be given to the temperature distributions and resulting gradients throughout the module as these exacerbate thermo-mechanical CTE-related failure modes. Thermal impedance dictates maximum T_j and operational limits, while ΔT drives cycle life reliability. Elemental metal baseplate and other components provide the highest thermal conductivities, but are associated with the largest CTE mismatch between die and substrate ceramics. The Gen I module design process involved detailed 2D analytical and 3D finite element analysis (FEA) modeling of selected components in order to balance T_{peak} and ΔT considerations. Comparisons were made between 3 different baseplate materials; AlSiC (η=180W/mK, 6.7 ppm/K), Cu (η=383 W/mK, 16.4 ppm/K), and a Cu-C metal matrix composite (MMC) composition with η^Z=200 W/mK, and CTE^{XY}=4 ppm/K. Direct bonded copper AlN (4.5 ppm/K) substrates were selected for both their thermal conductivity and close CTE match to the SiC die (3.8 ppm/K) and composite baseplates, and the previously mentioned SnAg die and substrate attach solder was also used. Table I summarizes the thermal impedance results of the 20 A die modeling efforts and includes the individual die and per-switch results for both MOSFET and JBS diodes. Also included in the table are the IGBT module values for an identically rated and packaged Powerex part. Differences between 2D and 3D calculations are due to the over simplified heat spreading and geometry assumptions of the 2D calculations. Coupled with FEA mechanical stress calculations, MMC Cu-C was identified as providing the best balance to η and CTE design considerations. Dielectric potting materials are also a critical concern for high temperature module reliability and operation. Two candidate (Wacker RT745S, NuSil R2188) high temperature silicone-based gels have accumulated over 570 hours at 1200V and 250°C with no increase in the baseline 1-4 μA leakage range. These gels have previously been shown to provide stable performance at 200°C and 10kV, and thus far appear suitable for up to 250°C environments.

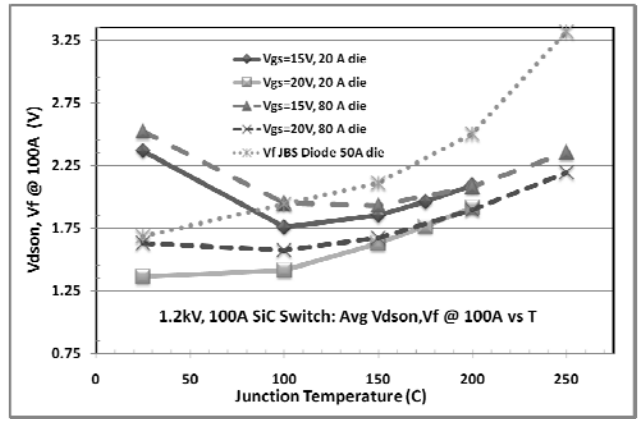

Figure 4. Average V_f characteristics for 20A and 80 A SiC MOSFETs and 50 A JBS diode module switches as f(T).

Material	Model	Single MOSFET (K/W)	MOSFET Switch (K/W)	Single JBS Diode (K/W)	JBS Diode Switch (K/W)
Copper	2-D	0.87	0.17	0.60	0.20
	3-D	0.62	0.12	0.46	0.15
AlSiC	2-D	1.36	0.27	0.94	0.31
	3-D	0.76	0.15	0.59	0.20
Cu-C MMC	2-D	1.23	0.25	0.85	0.28
	3-D	0.73	0.146	0.56	0.19
CM100DU	Data		0.15		0.29

Table I. Modeled thermal impedance results for selected module materials.

Performance Characterization. Fabricated phase-leg modules were subjected to static and dynamic testing to quantify operational performance characteristics. Inductively clamped double-pulse 500 V, 100 A switch testing and 100 A on-state conduction loss comparisons were made between SiC MOSFET dual modules and 1200 V, 100 A rated IGBT modules in identical module form factor. Switching loss analysis was conducted using third generation trench-gate high switching speed CM100DY-24NFH modules while conduction loss comparisons were performed using low-loss CM100DY-24NF parts.

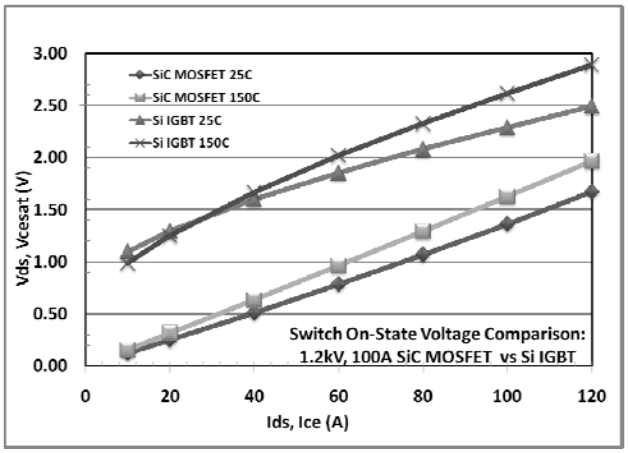

Figure 5. V_F as a function of Ic,Id comparing 1200 V SiC MOSFET-JBS diode module switches to 1200 V Si IBGT-PiN diode modules (CM100DY-24NF) at T=25°C, 150°C .

Fig. 5 illustrates typical conduction loss comparative data for one switch in the IGBT and MOSFET modules as a function of conduction current. The data reflects a significant reduction in on-state 100 A conduction losses of 41% and 38% at 25 and 150°C, respectively. At 200°C the SiC module losses increase approximately 20% above their 150°C value at I_D=100 A, but still remain below IGBT losses at 25°C. 100 A, 50% duty cycle dynamic loss characterization reflected the expected unipolar advantage of the MOSFET-JBS module switches over the CM100DY-24NFH bipolar Si technology, with the advantage becoming more pronounced at high temperatures due to the increasing IGBT and PiN minority carrier lifetimes. Table 2 summarizes the results of the loss analysis testing for both 25°C and 150°C temperatures, and reflects the significant advantage of SiC MOSFET power modules over comparable Si IGBT technology. In addition to electrical and loss characterization, modules are currently undergoing extensive reliability and qualification testing. Initial thermal shock, HTGB, HTRB, and power cycling test results reflect the sound design considerations and robust characteristics of these modules. Coupled with the superior electrical performance characteristics SiC MOSFET power modules have been shown to possess, this technology is highly suited for satisfy high efficiency, harsh environment applications.

	Conduction Loss (W)		Switch Loss (µJ)		Total Loss (W)	
	25°C	150°C	25°C	150°C	25°C	150°C
Si	114.5	131	12.6	18.2	366.5	495
SiC	68	81.5	9.5	7.3	258	227.5
% Reduction	40.61	37.79	24.6	59.89	29.6	54.04

Table 2. IGBT and SiC MOSFET switch and conduction loss summary

Summary

Design considerations and performance characteristics of initial 150°C Generation I SiC MOSFET power modules have been presented and shown to provide superior performance compared to existing Si IGBT components. Utilization of the selected robust design and materials yielded a 14% weight reduction, superior CTE match for cycle-life reliability, and minimal thermal performance penalty. The results achieved illustrate the maturity of SiC device technology and the potential to realize practical configurations capable of leveraging its' significant performance benefits.

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