Some Key Researches on SiC Device Technologies and their Predicted Advantages

SiC has proven to be a good candidate as a material for next generation power semiconductors. To analyse the advantages of SiC based power devices over their silicon counterparts, a high volume and standard application segment such as the 400 to 480VAC line rated motor drives is considered to be ideal. From this viewpoint, the present research work has focussed on 1200V class device technologies. 4H-SiC based MOSFET and SBD structures have been considered to be the best fit device configurations for the targeted application category. New SiC-MOSFET/SBD structures have been developed aiming at high power density applications. Performance details of such newly fabricated SiC devices, along with their evaluation under actual operating conditions, are also introduced. **Gourab Majumdar, Power Device Works, and Tatsuo Oomori, Advanced Technology R&D Centre, Mitsubishi Electric Corporation, Japan**

Silicon Carbide has been the focus of choice for advanced researches on post-silicon power semiconductor materials. In the last couple of decades, many of such researches have given promising results and have exhibited adequate technologies for device fabrication and characterisation (see Figure 1). However, practical devices that can aptly meet requirements from various power electronics applications are yet to be made available in volume. There are several key reasons for it. One is the problem of reducing the high cost involved in making the base SiC material and processing it for device

Material	Bandgap Energy	Dielectric Constant	Electron Mobility	Breakdown Electric Field	Saturated Electron Drift Velocity	Thermal Conductivity	FOM
	E_g	ε_r	μ_n	E_c	ν_{sat}	λ	
	eV	(dimension)	cm^2/Vs	$10^6 V/cm$	$10^7 cm/s$	W/cm.K	
Si	1.1	11.9	1500	0.3	1.0	1.5	1
GaN	3.4	9.5	900	2.6	2.5	1.3	407
3C-SiC	2.2	9.7	800	3.0	2.7	4.9	2381
4H-SiC	3.0	9.7	1000	3.5	2.7	4.9	3241
6H-SiC	2.9	9.7	460	3.0	2.0	4.9	1307

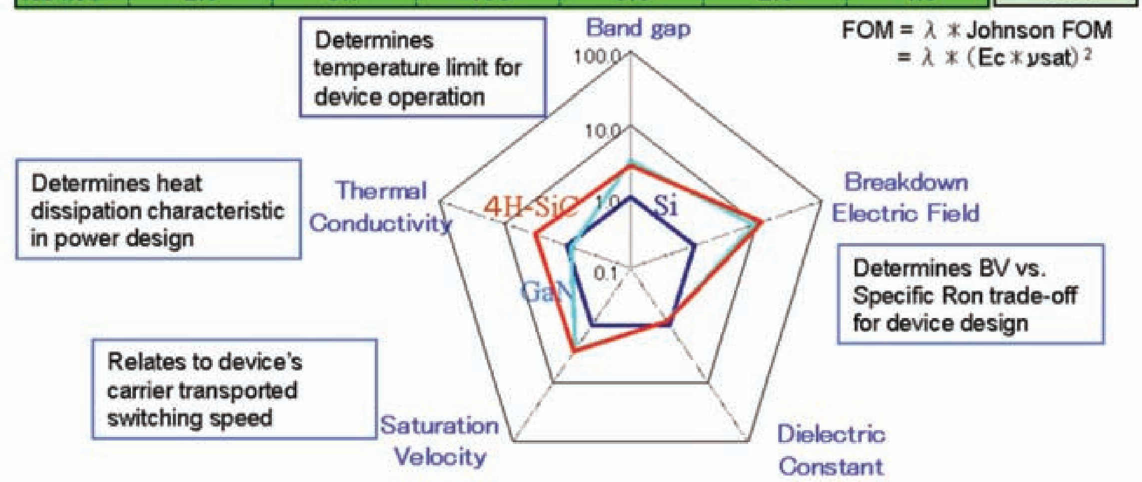


Figure 1: **Comparison of important physical properties of Si, GaN and three poly-types of SiC**

manufacturing, with sufficiently high yield and quality that can justify the theoretical advantages obtainable from the material's superior physical properties.

In our study, we have focused on finding SiC device solutions, in both configuration and characteristic aspects, that can properly meet requirements from the major power electronics application fields, such as the industrial motor drives segment, and can elevate systems' performance-to-cost ratio substantially.

Benefits from SiC application...

The appearance of SiC power devices on the market and in power electronics systems will accelerate new developments in the areas of device packaging, passive components, thermal design, circuit and system designs, as well as improvements in construction and operation of actuators, e.g. motor, transformers.

Figure1 also shows a radar chart comparison involving five most important properties of these materials. The FOM (figure-of-merit) values shown in the inserted table is based on Johnson's proposal, but uses thermal conductivity as an additional multiplier to make the figure more realistic for power applications. As reveals, the 4H-SiC excels in terms of the defined FOM and this poly-type of the material has become the focus of attention.

The above explained physical properties of high electric field breakdown in combination with other items considered in the FOM translate into improved efficiency, dynamic performance and reliability of power electronics systems. Thus, SiC power devices are expected to be used in various fields of power electronics equipment in the near future, provided that their performance advancement and introductions become justifiable from the applied systems' performance-to-cost ratio.

...For power devices

In Figure 1, some important physical properties of SiC that are significant for its application as power semiconductor material are compared with those of the existing Silicon and GaN, which is also considered as another potential candidate for the purpose from the WBG (wide bandgap) material choices.

The main thrust in this advancement has been given by the excellent improvement achieved in MOS-gated power semiconductor device technologies including IGBTs and IPMs (Intelligent Power Modules). Figure 2 shows a chronology of state-of-the-art power electronic systems' output power density growth in an average over a 1 to 100kW range. At present, 3 to 5W/cm³ power density is the level achieved in commercial equipment. In a decade, more than 10 times of the present level is considered to be achievable. The major portion of power electronic systems' volume comes from the size of the passive components and heatsinks.

In general, SiC power semiconductor devices have the advantage of lower loss, even at very high frequency switching operation, and can work at a very high junction temperature condition. In addition, by using unipolar SBDs (Schottky Barrier Diodes) instead of PiN diodes for freewheeling operation in hard switched bridge circuits, reverse recovery can be minimised drastically reducing EMI noise generation to a very good extent. In short, SiC devices are expected to play a prime role in future system designs where low conduction losses, low switching losses at high switching frequency and a high working temperature above 200°C would be essential for significantly advancing systems' performance. The predicted advantages of introducing SiC power semiconductor devices in various power electronics systems are summarised in Figure 3 [1,2,3] .

Status of SiC devices

Many researchers have investigated various SiC devices such as SBDs, pin rectifiers, MOSFETs, JFETs (junction field

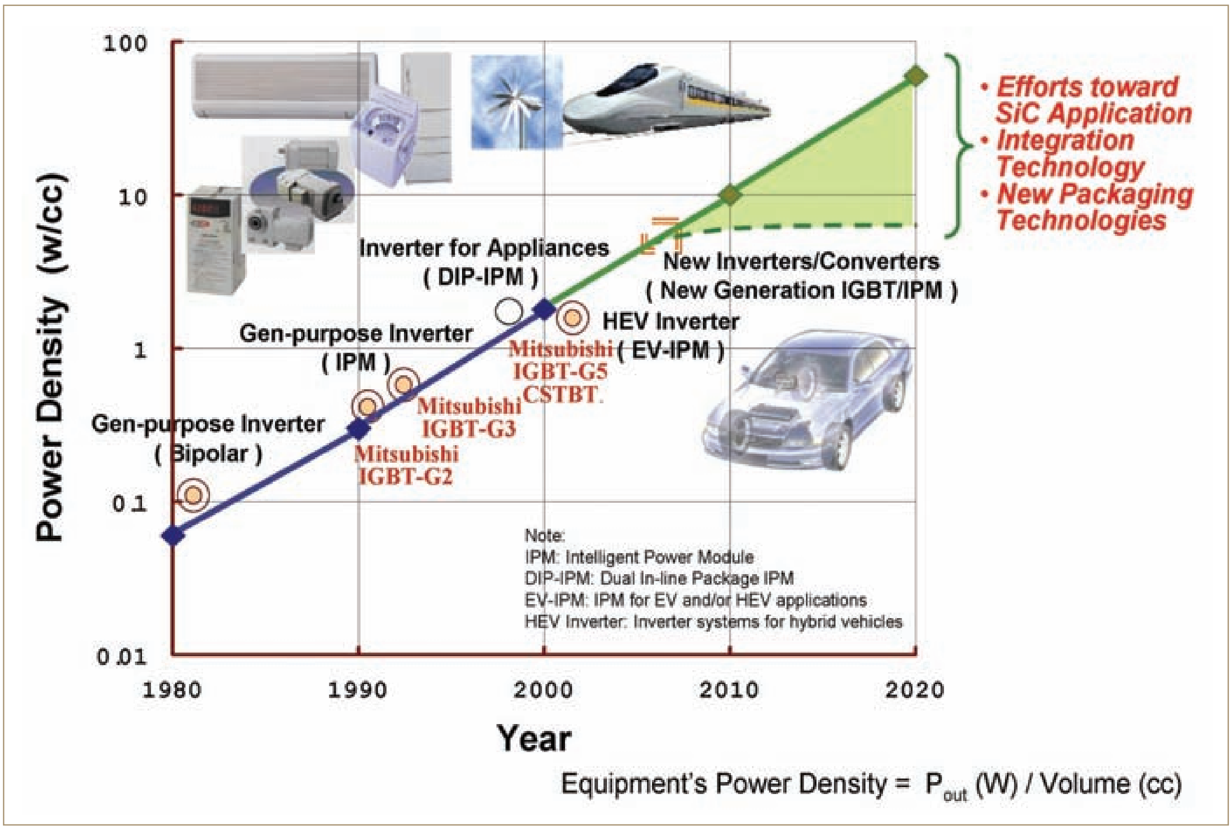


Figure 2: Growth of power density in power electronics system designs and its projection, also indicating the power semiconductor technologies that have been the key contributors in this trend and future expectations

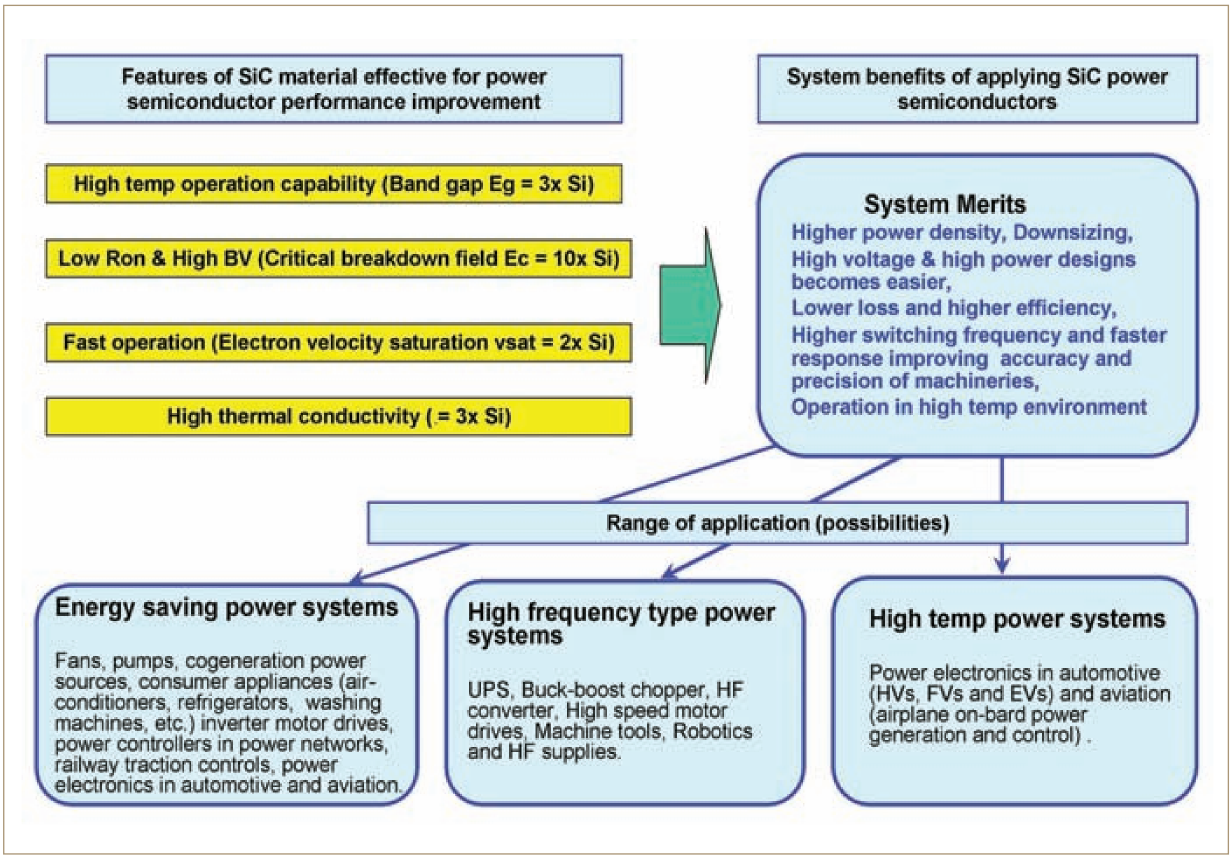
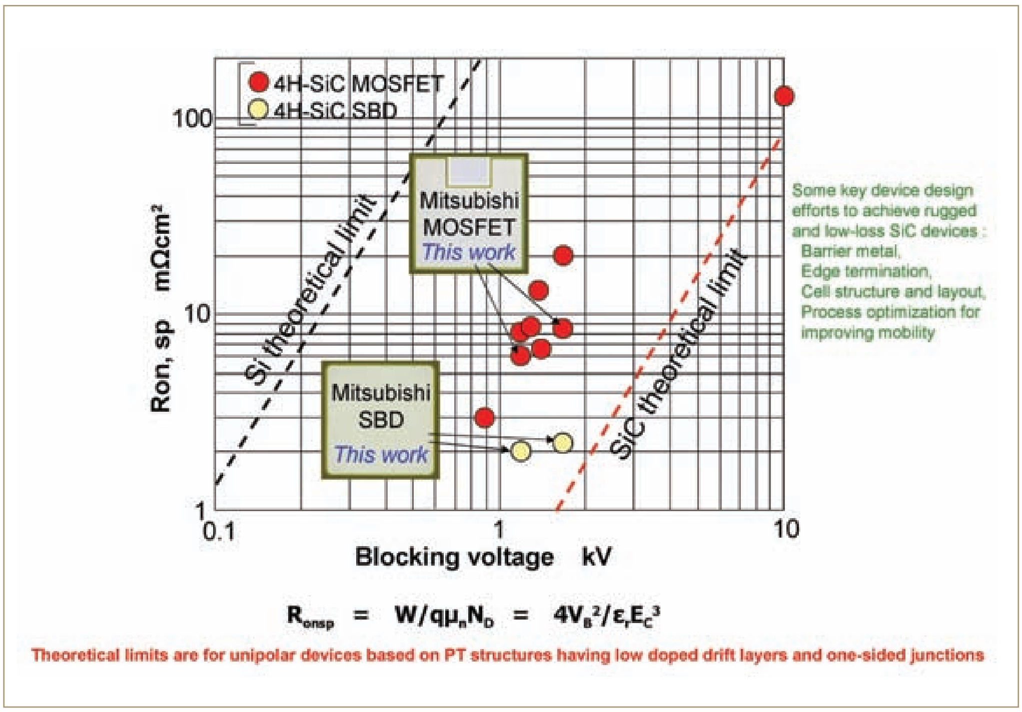


Figure 3: The important features of SiC material for power semiconductor applications and the benefits that can be derived from such features for a range of power electronics applications

effect transistors), MOSHFETs (MOS hetero-junction FETs, BJTs (bipolar junction transistors) and IGBTs. High voltage capability has been demonstrated in almost all types of SiC power devices that have been experimented under various research programs worldwide. The progress in terms of voltage blocking capability has depended on the availability of low doped thick epitaxial layers and improvements in the process steps and equipment for device fabrication. In the case of diode structures, significantly low on-resistance values have been achieved.

In terms of blocking voltage, SBDs have been fabricated having breakdown voltage as high as 5kV. PiN diodes have been experimented for even higher voltage range. However, PiN diodes with blocking voltage above several thousand volts will require significant improvement of carrier lifetime in the low doped region of the device structure. Also, with a thick low

Figure 4: Specific on-resistance versus blocking voltage achieved using 4H-SiC for SBD and MOSFET fabrication (W and μ_n are respectively the width and carrier mobility of the drift region, and ε_r and E_c are respectively the dielectric constant and critical breakdown electric field of the material)



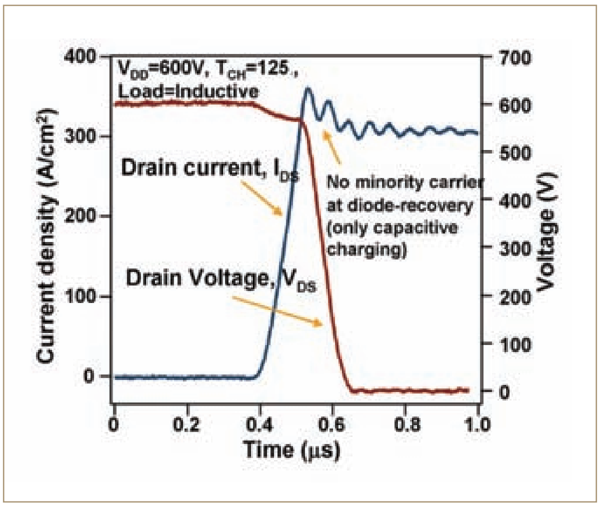


Figure 5: High current density turn-on switching performance of a new 4H-SiC MOSFET and a new 4H-SiC-SBD, both rated 1200V/25A, in a hard-switched inverter bridge circuit

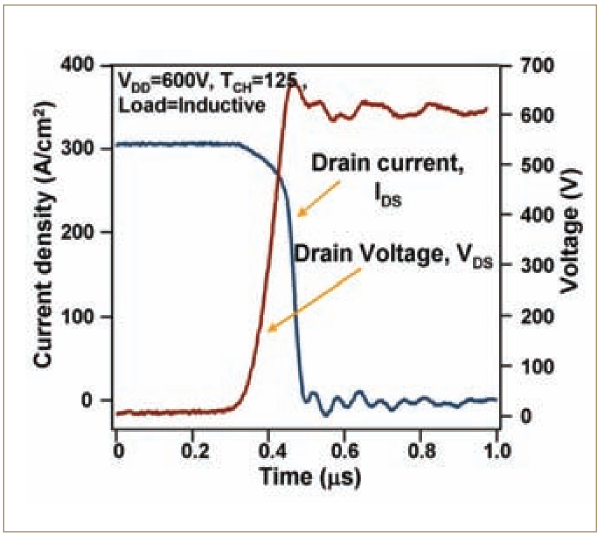


Figure 6: High current density turn-off switching performance of a new 4H-SiC MOSFET and a new 4H-SiC-SBD, both rated 1200V/25A, in a hard-switched inverter bridge circuit

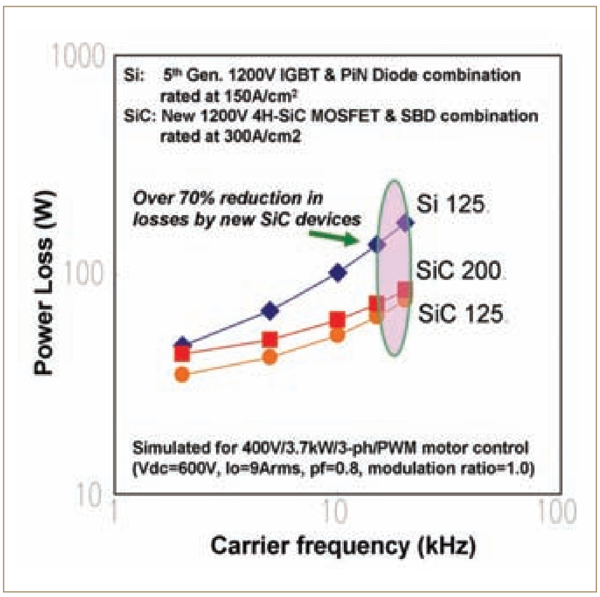


Figure 7: Power loss estimation for inverter operation at high current density

doped drift layer for such high voltage structures using SiC, stacking faults originated from the so called basal-plane-dislocations are considered to cause a forward voltage drop drifting over time due to their recombination driven movements.

In the case of transistor like controllable switching structures, JFET type devices have exhibited fairly low on-resistance, even with a high breakdown voltage capability. However, JFET is a normally-on type power switch and, due to that functional feature, it faces many restrictions in power control circuit applications.

For voltage classes up to about 3kV range, SiCMOSFETs are expected to play a key role due to its normally-off feature and simplicity in control requirement attributed to the virtues of its insulated gate structure, sufficient ruggedness and comparatively easier manufacturability. However, the on-resistance of experimental SiC MOSFETs has often shown much higher than the theoretical value predictable from SiC's physical properties. This is primarily attributed to a large amount of defect density generated at SiC/SiO_2 interfaces around the three-channel region. The density of defects (trap density) thus generated, causes the carrier mobility to go down, decreasing current conduction capability and increasing on-resistance. Considering an n-channel 1200V SiC MOSFET, a channel mobility of 50cm²/Vs for electrons would be essential to reduce the on-resistance of the device to a sufficiently low value.

Improved static performance of SiC devices

In our research, we have focused on developing 1200 to 1700V range SiC device technologies that can also realise sufficiently large current output type power chips. For this purpose, the two aforementioned key device structures, namely the power MOSFET and the SBD, have been chosen as these are considered to provide optimum functionality in all power circuit topologies applied in the targeted application zone, although there have been several process and structure related issues. Concerning SiC-MOSFET, the problem of low channel mobility has been thoroughly investigated.

A remarkable channel mobility improvement has been made by developing an appropriate cell structure and an advanced channel implantation process step. With the result, a substantial gain in terms of specific on-resistance (R_{on-sp}) versus breakdown (blocking) voltage, BV trade-off performance has been achieved for both 1200 and 1700V rating categories, as shown in Figure 4. Each theoretical limit shown is applicable for a low doped drift layer with one-sided junction designed for punch-through operation in blocking mode and majority carrier current in conduction mode, using either Si or 4H-SiC.

Concerning SiC SBD structures, many efforts have gone in to optimising barrier metal formation and metallisation processes for obtaining low forward voltage characteristic, active area and electrode designs for sufficiently high current density operation, and chip edge

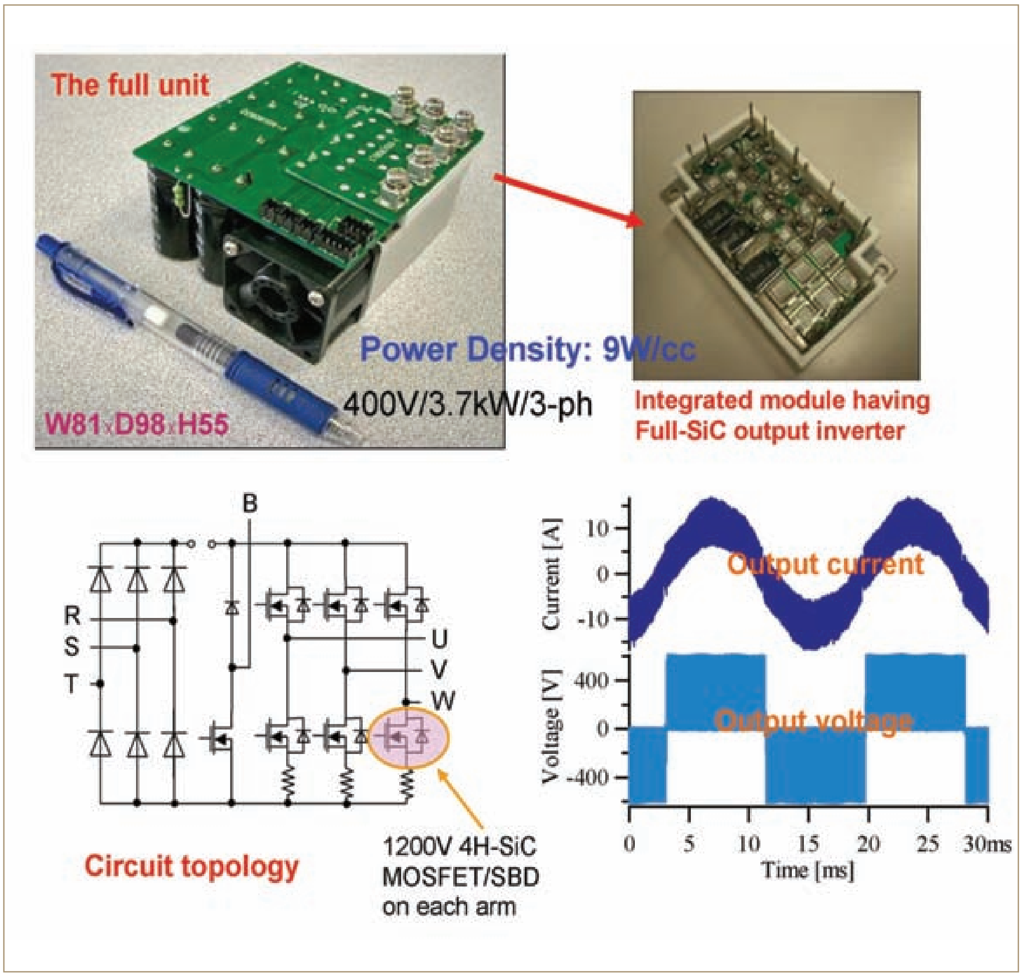


Figure 8: 3.7kW/400V three-phase full SiC inverter and operational waveforms demonstrating its capability to operate at a very high power density (9W/cm³)

design for sustaining electric field at any high voltage bias condition. The latest SBD structures obtained through our present work exhibit low differential on-resistances at both 1200 and 1700V categories. Thus, the trade-off points in terms of specific on-resistance and breakdown voltage are remarkably close to the theoretical limit for 4H-SiC shown in Figure 4.

Improved dynamic performance of SiC devices

These experimental SBD chips have also been stressed to very high current density in dynamic mode and are found to have ruggedness higher than 1700A/cm².For forming a standard arm switch suitable for hard-switched inverters, the fabricated 1200V SiC MOSFET and SiC SBD chips were tested in a inductive load bridge circuit topology. Figures 5 and 6 exhibit the combined performance at a high current density condition in the test set-up. The transient energies per pulse of switching operation are found to be independent of channel/junction temperature variation due to both devices being free of conductivity modulation and thus, the combination is considered to be a very effective

choice for high frequency operated inverter bridge circuits, where switching losses dominates conduction losses. In order to confirm this observation, loss simulation for actual inverter operation has been carried out and the results are shown in Figure 7.

As expected, the power loss value for the combination using Si IGBT and Si PiN diode increases more rapidly than the combination using 4H-SiC MOSFET and 4H-SiC SBD. Also, the power losses of SiC devices do not vary significantly with channel temperature, particularly at high carrier frequency range. This also emphasises the predicted effectiveness of using SiC power devices where a high switching frequency is advantageous for designing the whole system.

Using these new high current density type 4HSiC-based MOSFET and SBD chips, power conversion modules and inverter units have been built for experimental purposes. Figure 8 shows one of such units designed to drive a 3.7kW/400V three-phase AC motor. With the SiC-based output the inverter switches at 15kHz, the power density achieved at full load is typically 9W/cm³, which is considerably high for this class of application system investigated under the present work.

Conclusion

Possible benefits from use of SiC power devices have been analysed and choices of device configurations for hard-switched power conversion systems have been discussed.

Both in terms of static and dynamic performances, the latest 4H-SiC-based MOSFET and SBD power chips have demonstrated high power handling capability, even at high temperature and high switching frequency operating conditions. All these outcomes imply that SiC power devices are promising candidates for power electronics applications where higher power density and energy saving designs are increasingly demanded.

Literature

[1] Y. Hayashi, K. Takao, T. Shimizu and H. Ohashi: High Power Density Design Methodology, 2007 IEEE, 569-574

[2] C.M. Johnson: Comparison of Silicon and Silicon Carbide Semiconductors for a 10kV Switching Application, IEEE-PESC Proc. 2004, 572-578

[3] G. Majumdar: Future of Power Semiconductors, IEEE-PESC Proc. 2004, 10-15, 2004