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Progress in SiC Power Semiconductor Devices

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1. Introduction

For the last 50 years the power electronics industry has relied on Si semiconductor devices. However, the physical limitations of Si have triggered the development of wide bandgap semiconductors, including SiC.

Currently there is a shift in the production of SiC wafers from three to four and six inches. Micropipe densities have been dramatically reduced, and the main efforts to improve the crystal quality are being shifted to reduce other micro-defects, such as basal plane, screw and threading edge dislocations. Within the last ten years, high performance characteristics have been demonstrated for a wide range of device structures. This paper presents an overview of the present status and future prospects of SiC power semiconductor devices, which are progressing steadily towards practical application.

2. Positioning of SiC power devices

The breakdown electric field (E_c) of SiC is about ten times that of Si (E_c(4H) = 2.7MV/cm), and that offers the following advantages of SiC power devices over Si counterparts: (1) the thickness of the drift layer of SiC can be reduced to 1/10 of that of Si, and also higher doping is possible to the drift layer of SiC, those combined enable reduction of the drift layer resistance to 1/300 that of Si in unipolar devices; and (2) the use of the same drift layer thickness as Si enables a blocking voltage of ten times that of Si. The characteristics (1) would enable further reduction of the on-resistance of unipolar devices as well raising the possibility of using unipolar SiC power devices above 600 V, which would contribute to reducing the size of inductive and capacitive components of power supplies. The characteristics (2) would enable the fabrication of devices operating at ultra-high blocking voltages (> 10kV) and it would be possible to reduce the number of series connected devices required for construction of high power converter systems. Further, the wide bandgap of SiC (E_g(4H)=3.26eV) enables high temperature operation, and its high thermal conductivity compatible with copper (4.9 W/cmK) is useful for effective cooling, which lead to the construction of compact power supplies.

3. SiC Diodes

Schottky barrier diodes are unipolar devices, which exploit the full potential of the physical properties of SiC. It has come to obtain characteristics near the unipolar limit of 4H-SiC. Medium voltage class SBDs (600-1700V, 1-30A) are being already commercialized, and used in switching mode power supplies and demonstrated in various power conversion units. The hybrid-pair of a Si-IGBT/Si-MOSFET and a SiC-SBD is the surest method in present stage to reduce power-loss of power supplies. The hybrid-pair configuration enables over 30% reduction in the total power loss compared with all Si solution. The manufacturing yield of SiC-SBDs has risen as the quality of SiC wafer is improved. Large current SiC-SBD (300A, 10mm x 10mm) was also reported.

PiN diodes are being studied as devices with reverse blocking voltages greater than 4 kV , where on-state voltages of greater than 3 V are accepted. The highest blocking voltage of SiC-PiN diode is 19.5 kV (epilayer thickness = 200 μm). Although SiC-PiN diodes have suffered from the on-state voltage degradation problem due to crystal defects, it has been almost solved.

4. SiC Switching Devices

MOSFET and JFET are the present main battlefield of the SiC power device research and development. Medium voltage class MOSFETs and JFETs (600-1700V) with specific on-resistance of less than 5 mΩcm^2 (RT) came to be reported. The improvement of crystal quality and oxidation method is advanced aggressively to secure the reliability of the gate oxide layer.

Minimum values for the specific on-resistance (700V1.01mΩcm^2, 1270V1.21mΩcm^2, 1570V2.8mΩcm^2 (normally-off type)) were reported using an SIT/JFET structure. Small specific on-resistances are demonstrated also in MOSFET structure by reducing the unit cell size, increasing the mobility of the MOS channel itself and reducing the parasitic resistance.

The reported high performance SiC-MOSFETs are as follows: (1) IEMOSFET (Implantation and Epitaxial MOSFET), 1100V4.3mΩcm^2 for Si face, 660V1.8mΩcm^2 for C face, (2) DIMOSFET (Double Implantation MOSFET), 900V3.1mΩcm^2 for Si face, 1360V5.0mΩcm^2 for C face, (3) Trench gate MOSFET, 790V1.7mΩcm^2. Although these values are drastically improved in recent years, they must be further improved to meet industrial application requirements (specific on-resistance of 1–2mΩcm^2).

5. Impacts on power electronics applications

There are two major system impacts of SiC power devices, namely, high efficiency and high power density (Fig. 1). More than 30% of total power loss is decreased by using the hybrid-pair configuration, and more than 80% could be decreased by all SiC configuration. The smaller power-loss and higher frequency lead to smaller cooling units and smaller passive components. It enables compact and low price power supplies.

Recent reports on the application field are as follows: (1) 90% of power-loss reduction in 20kW all-SiC inverter using 1200V60A SiC-MOSFETs and SiC-SBDs, (2) 280kW all-SiC inverter module (1200V230A), (3) 200kVA all-SiC inverter using 4.5kV100A SiCGT.

Figure 2 shows the market size for power devices. The present market size of total power devices is 13B$/year. The potential applications for SiC power semiconductor devices are medium (25%) and High voltage (15%) application area. As SiC power semiconductor devices become to handle larger power with higher reliability and lower cost, the application field of SiC power semiconductor devices will expand.

6. Conclusions

The current status of SiC power semiconductor devices has been reviewed. The improvement of wafer quality boosts the current ratings of SBDs up to 100A. The hybrid-pair of Si switching devices and SiC-SBDs are the surest method in present stage to acquire the benefit from SiC. Although the performance of MOSFETs has been dramatically improved, there still remains reliability problem to be solved to commercialize MOSFETs. While great progress has been demonstrated, much more work should be done including assembly and control technology to enable the commercial success of SiC power devices.

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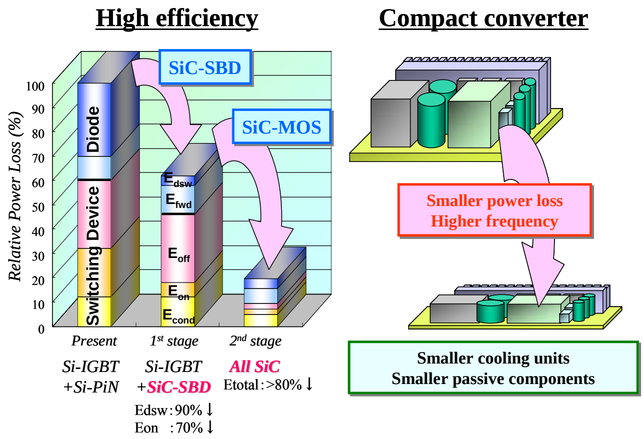

Fig. 1 Two major system impacts of SiC power devices.

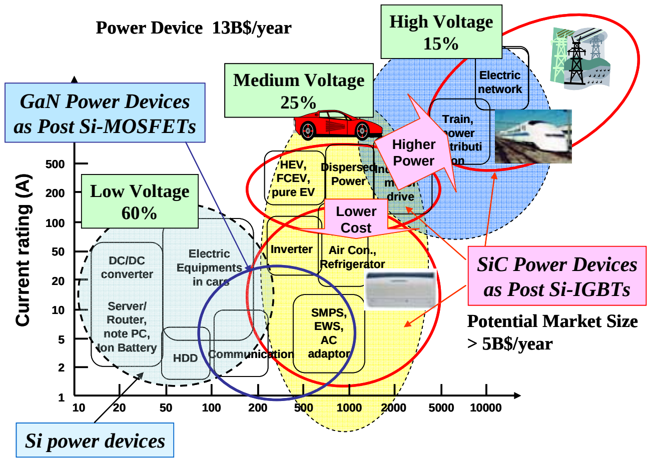

Fig. 2 Potential Market Size for SiC power devices.