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Semiconductor Silicon Carbide for Power Electronic Application

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Device-quality homoepitaxial SiC crystals have been grown by atmospheric vapor phase epitaxy on off-oriented substrates prepared by a sublimation method. Recently, high-voltage p-n junction and Schottky rectifiers, MESFET's, MOSFET's, and thyristors have been demonstrated utilizing high-quality SiC epitaxial layers. The present advanced stage of SiC crystal growth techniques and the state-of-the-art SiC high-power device application are presented.

1.INTRODUCTION

Development of semiconductor materials to realize higher power and frequency devices in the power-electronics field, where Si is not adequate because of the limit of inherent properties, has been strongly required in these days.

Silicon carbide (SiC) has been regarded as a promising semiconductor material for high-power devices, owing to its excellent electrical properties [1-3]. Recently, 1-inch wafers of 6H- and 4H-SiC grown by a sublimation method have been commercially available, and high-quality homoepitaxial layers have been obtained by means of a vapor phase epitaxial growth technique [4-6]. Thus, the research on SiC applying to power devices has become active, and the number of reports on them has been increasing year by year [7-14].

In this report, high-quality crystal growth of 6H- and 4H-SiC and those excellent electrical properties are introduced. The state-of-the-art SiC high-power devices utilizing the high-quality epilayers are presented.

2.CRYSTAL GROWTH AND ELECTRICAL PROPERTIES OF SiC

6H- and 4H-SiC homoepitaxial layers are grown on off-oriented 6H- and 4H-SiC {0001} substrates by VPE at 1500°C, which is called "step-controlled epitaxy" [15,16]. The density of surface steps is increased by angle lapping, and utilizing step-flow growth, the polytype-controlled epitaxy at low temperatures can be realized. Crystal quality of substrates has been improved, and step-controlled epitaxial growth condition has been optimized. As a result, high-purity and high-quality single crystals have been obtained in these days [5,6,17].

Figure 1 shows the temperature dependence of electron mobility in step-controlled epitaxial 6H- and 4H-SiC {0001} planes. An electron mobility as high as 720cm^2/Vs was obtained at 292K in 4H-SiC epilayers with a carrier concentration of $\sim 2\times10^{16}$cm^{-3}. At 77K, the electron mobility increased up to 11,000 cm^2/Vs. Besides, the electron mobility of 4H-SiC is about two times higher than 6H-SiC (380cm^2/Vs) in the {0001} plane. The breakdown field versus donor concentration of 6H- and 4H-SiC is shown in Fig.2.

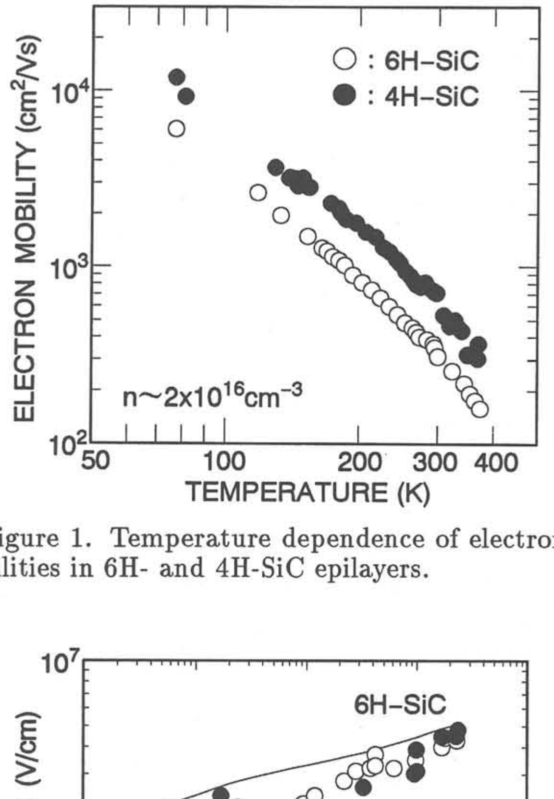

Figure 1. Temperature dependence of electron mobilities in 6H- and 4H-SiC epilayers.

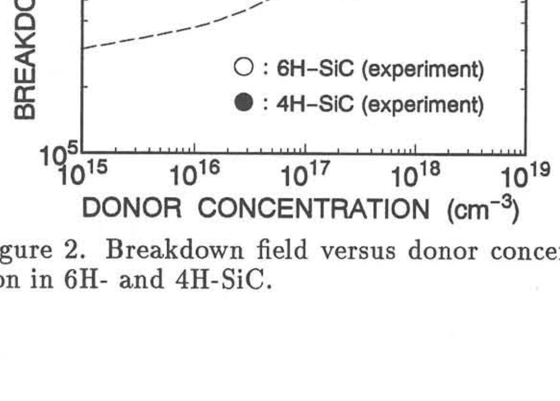

Figure 2. Breakdown field versus donor concentration in 6H- and 4H-SiC.

The solid curve denotes the values reported in 6H-SiC previously [18], and the broken curve the values in Si. The high breakdown fields ($\sim 3\times10^6$V/cm) were obtained, and there are no significant differences in the breakdown fields between 6H- and 4H-SiC.

Baliga has reported the figure of merit for high power devices [19], and higher electron mobility and breakdown field are more suitable for high-power device applications. From the above results, SiC can be regarded as the most hopeful material for high-power devices, and 4H-SiC is superior to 6H-SiC.

3.FEASIBLE SiC POWER DEVICES

3.1 High-Voltage P-N Junction Rectifiers

6H-SiC p-n junction diodes were fabricated in 6H-SiC epilayers grown by VPE, and utilizing high-purity n-type regions ($N_d \simeq 10^{14} \sim 10^{15}$cm^{-3}), the breakdown voltages increased up to 2.0~4.5kV [20,21]. The above result reflects the significant improvement of purity and quality in SiC epilayers.

3.2 High-Power Transistors

The theoretical analysis of SiC MESFET's has been carried out, and high output power at high frequency (65W at 10GHz) has been predicted in 6H-SiC MESFET's by Trew et al [1]. Sriram et al. have reported that 6H-SiC MESFET's showed high f_{max} of 25GHz and RF gain of 8.5 dB at 10GHz, while operating at a high drain voltage of 40V [12]. As for 4H-SiC MESFET's, the device having f_{max} of 12.9GHz and RF gain of 9.3dB at 5GHz (2.2dB at 10GHz) has been reported by Weitzel et al [13]. The output power density was 2.8W/mm at 1.8GHz with a high drain voltage of 54V.

SiC MOSFET's have also been considered for the use in high-power application due to their high-speed switching and low power-loss characteristics. Recently, the vertical power UMOSFET structures in both 6H- and 4H-SiC were reported by Palmour et al [14,18,22]. The 6H-SiC UMOSFET's showed a maximum transconductance (g_{max}) of 6.75mS/mm and a threshold voltage of 3.7V. The devices withstood current densities of 190A/cm^2. On the other hand, the 4H-SiC UMOSFET's withstood 550A/cm^2 and power densities greater than 10kW/cm^2. The specific on-resistance was $17.5\times10^{-3}\Omega$cm^2. The g_{max} for this device was about 10mS/mm, and a highest blocking voltage of 180V could be realized. These 6H- and 4H-SiC UMOSFET's operated well up to 300°C.

3.3 Thyristors

Bipolar power device structures have also been reported, and these had collector voltages as high as 200V and current gains as high as 10.4 [18]. Additionally, both 6H- and 4H-SiC npnp thyristors have been demonstrated [18,22]. The devices based on 6H-SiC showed forward and reverse voltages of 160V with no gate current. The forward breakover voltage was reduced to -6V with a trigger current of -200μA. The built-in voltage and specific on-resistance were 2.65V and $3.6\times10^{-3}\Omega$cm^2, respectively. These devices operated well up to 500°C. For 4H-SiC npnp thyristors, forward and reverse blocking voltages of 210V with no gate current were realized. The forward breakover voltage was much reduced to -3.1V with a trigger current of -500μA. The built-in voltage of 2.85V was higher than 6H-SiC. The specific on-resistance of $1.75\times10^{-3}\Omega$cm^2 was obtained, however. The improved on-resistance results in a lower voltage drop for high current density in spite of higher built-in voltage as compared with 6H-SiC.

4.HIGH-PERFORMANCE SiC SCHOTTKY RECTIFIERS

In high-voltage switching devices, Schottky rectifiers are useful to realize high-speed switching characteristics as compared with p-n junction rectifiers because the carrier transport is mainly due to majority carriers and accumulation time of minority carriers is irrelevant in Schottky rectifiers. Furthermore, using SiC, high blocking voltage characteristics would be realized with thin drift layers, which leads to being low specific on-resistances.

High-voltage (>1.1kV) Au/6H-SiC Schottky rectifiers were fabricated by our group [8]. The rectifiers showed the low specific on-resistances of $\sim 8\times10^{-3}\Omega$cm^2. The high-temperature operation was realized at 400°C keeping low specific on-resistances which had a temperature dependence of $T^{2.0}$. Recently, further reduction of specific on-resistances could be realized utilizing 4H-SiC Schottky rectifiers keeping high blocking voltage characteristics as shown in Fig.3 [9,10]. The broken and solid curves denote the theoretical limits for Si, 6H-, and 4H-SiC rectifiers. The high blocking voltages ($\sim$1kV) 4H-SiC Schottky rectifiers with specific on-resistances of $\sim 1\times10^{-3}\Omega$cm^2 were fabricated. These rectifiers showed high-speed switching characteristics [23]. From the theoretical analysis of power loss,

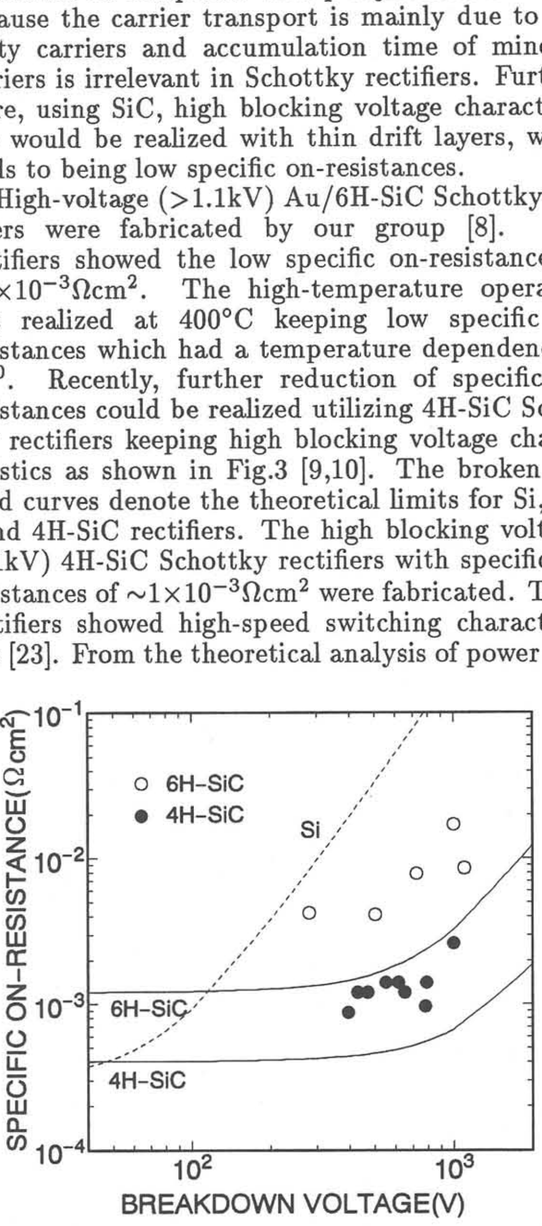

Figure 3. Specific on-resistance versus breakdown voltage in Si, 6H-, and 4H-SiC.

the optimization of Schottky barrier height is crucially needed to reduce the power loss as low as possible. Ti/4H-SiC Schottky rectifiers showed the most efficient characteristics [10,23]. The edge termination was employed using ion implantation technique [9,23], so that the blocking voltages increased up to ideal values, and reverse bias characteristics were improved as shown in Fig.4.

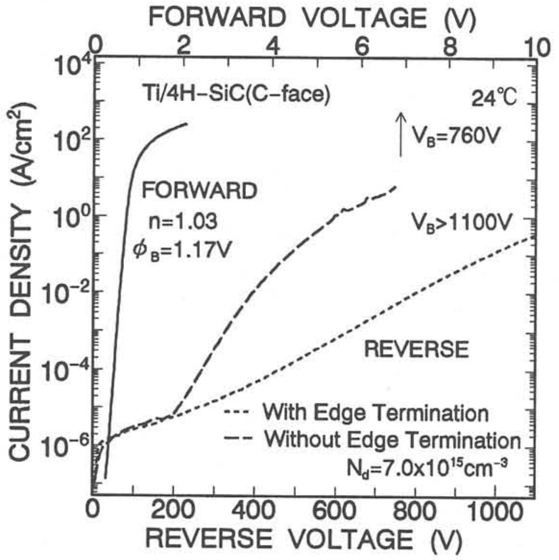

Figure 4. Current-voltage characteristics in Ti/4H-SiC Schottky rectifiers with/without edge termination.

5.SUMMARY

Recent progress in crystal growth techniques and power device application technology for SiC is remarkable. High-voltage and high-power devices requiring high-frequency and high-temperature operation, which can not be realized using Si, have been realized in these days. SiC-based high-power devices will be made fit for practical use in the near future.

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