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Recent Progress in SiC Ion Implantation and MOS Technologies for High Power Devices

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1. Introduction

Silicon carbide (SiC) has received increasing attention as a vital wide bandgap semiconductor projected for high-power, high-frequency, and high-temperature electronics. In addition to the distinguished properties, SiC is an exceptional wide bandgap semiconductor in a sense that both n- and p-type conductivities can easily be controlled in a wide range. SiC is the only compound semiconductor which forms high-quality SiO_2 by thermal oxidation like in Si, enabling the fabrication of MOSFETs.

Recent breakthroughs in crystal growth technology have led to the availability of high-quality SiC materials, with which outstanding potential of SiC has been demonstrated in prototype devices such as high-voltage diodes, vertical MOSFETs, high-power microwave MESFETs, and ICs operating at high temperature [1]. In this paper, recent progress in fundamental issues on SiC epitaxial pn junction, ion implantation, and MOS technologies is discussed.

2. High-Voltage Epitaxial pin Diode

The authors have succeeded in epitaxial growth of thick and high-purity SiC by chemical vapor deposition (CVD) [2]. The improvements of susceptor design and growth process enabled to grow 30~50 μm-thick SiC epilayers with a low net donor concentration of $1\sim3\times10^{14}$ cm^{-3}. Figure 1 depicts the current density-voltage characteristics of an epitaxially grown SiC(0001) pin diode with a 31 μm-thick *i*-layer. The diode exhibited a very high breakdown voltage of 4200 V with a low on-resistance of 4.6 $m\Omega cm^2$. This result is plotted in Fig.2, where the theoretical limits of specific on-resistance for Si and SiC unipolar devices are shown as a function of breakdown voltage. The present data has greatly exceeded not only the limit of SiC unipolar devices, owing to the effective conductivity modulation, but also the performance of commercial Si pin diodes with the same blocking voltage. The diffusion length of minority carriers was estimated to be 11 μm, indicating the high-quality of the material.

3. Ion Implantation and pn Diode

Phosphorous (P) ion implantation at elevated temperature is effective to form heavily doped n^+ region with a sheet resistance as low as 100 Ω/□. High-dose aluminum (Al) ion implantation for p^+ doping has still resulted in a relatively high sheet resistance of 6300 Ω/□, being a future challenge.

MeV aluminum and boron (B) ion implantations into SiC have been investigated to form 3 μm-deep pn junction for future kV-class DIMOSFET and IGBT fabrication. The 3 μm-deep box profiles were created by multiple Al (50 keV-6.2 MeV) or B (30 keV-3.4 MeV) implantations with a total dose of $3.0\times10^{14}cm^{-2}$. High blocking voltages over 3000V and low leakage current density of $10^{-8}\sim10^{-7}$ A/cm^2 at −1000 V could be achieved for MeV-implanted and 1800°C-annealed mesa pn diodes with 15 μm-thick n^- layers. Furthermore, these diodes could withstand high avalanche current density up to 2 A/cm^2 at −3000V, indicating excellent robustness of SiC devices. Figure 3 represents the ratio of average blocking voltage measured and ideal blocking voltage calculated from the diode structure, for Al^+- or B^+-implanted SiC pn diodes annealed at two different temperatures. Annealing at 1800°C has significantly improved the blocking performance, and more than 80% of parallel-plane breakdown voltage has been realized.

4. High-Performance MOSFET

High channel mobilities of 96 and 116 cm^2/Vs have been attained for inversion-type 4H- and 6H-SiC MOSFETs fabricated on SiC(11$\bar{2}$0), respectively [3]. Figure 4 shows the temperature dependencies of (a) channel mobility and (b) threshold voltage for 4H-SiC(11$\bar{2}$0) and (0001) MOSFETs. The channel mobility of 4H-SiC(11$\bar{2}$0) MOSFET decreased

according to the $T^{-2.2}$ dependence above 200 K, whereas the mobility on SiC(0001) increased at elevated temperature, demonstrating superior MOS interface quality on $(11\bar{2}0)$ face. The threshold voltage of 4H-SiC(0001) MOSFET is very high, 7.8 V at room temperature, and it greatly decreases down to 2.7 V at 500 K, which is accompanied with the increased channel mobility. In contrast, the threshold voltage of 4H-SiC$(11\bar{2}0)$ MOSFET is lower, 4.0 V, and is insensitive to temperature. Recent study demonstrates much lower interface state density near the conduction band edge on $(11\bar{2}0)$.

5. Summary

Through recent demonstration of striking SiC power devices, the size, quality, and costs of SiC wafers have been recognized as crucial issues for wide commercialization of SiC electronic devices.

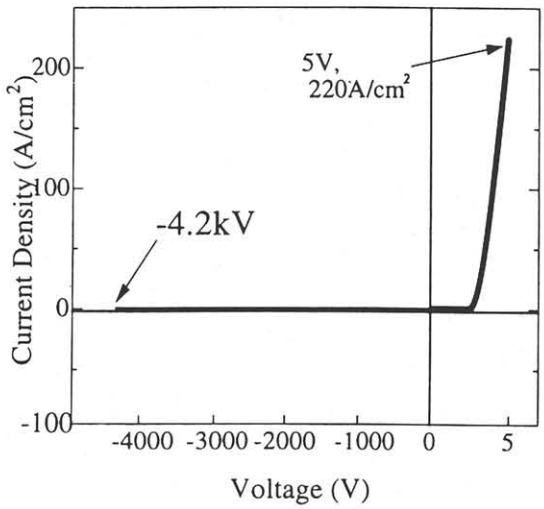

Fig. 1 Current density- voltage characteristics of an epitaxially grown SiC(0001) pin diode.

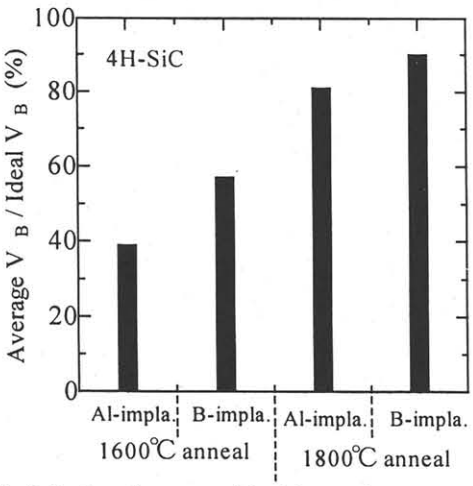

Fig.3 Ratio of average blocking voltage measured and ideal blocking voltage for four types of SiC pn diodes formed by MeV Al^+ or B^+ implantation.

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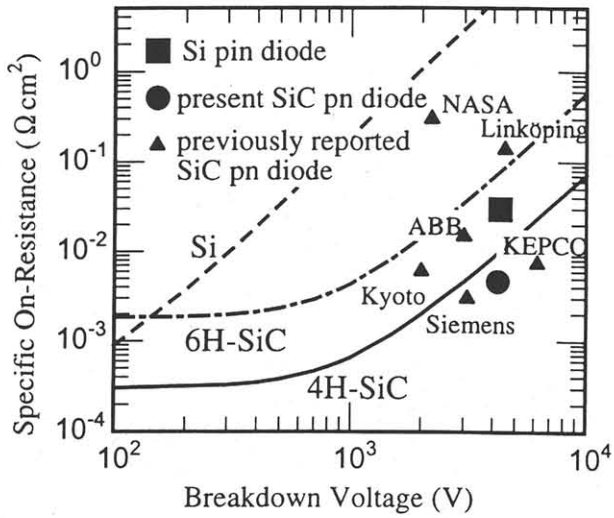

Fig.2 On-resistance vs. breakdown voltage for recent Si and SiC pin diodes together with theoretical limits of Si and SiC unipolar devices (curves).

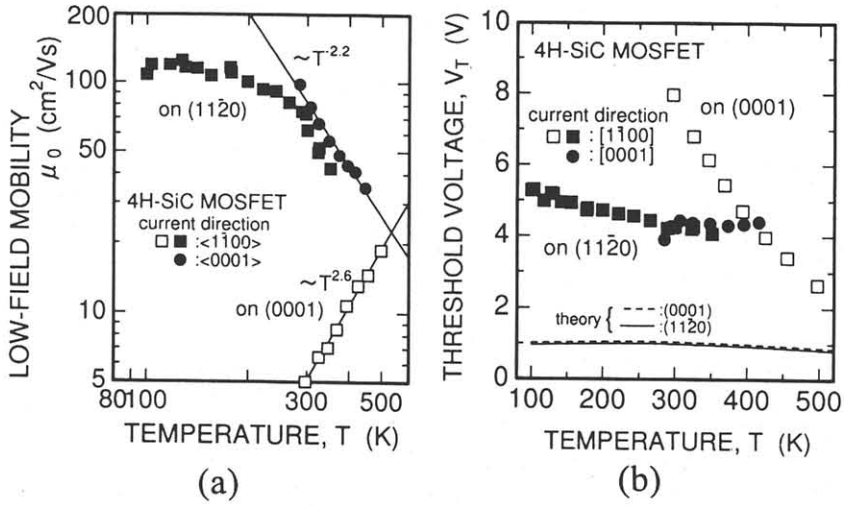

Fig.4 Temperature dependencies of (a) channel mobility and (b) threshold voltage for 4H-SiC$(11\bar{2}0)$ and (0001) MOSFETs.