Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 814-816

SiC Schottky Barrier Diodes with High Blocking Voltage of 1kV

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Au/6H-SiC Schottky barrier diodes were fabricated using layers homoepitaxially grown on 6H-SiC substrates by step-controlled epitaxy. A breakdown voltage over 1100V could be achieved, which is the highest value ever reported for SiC Schottky barrier diodes. These high-voltage SiC rectifiers had low specific on-resistances lower than the theoretical limits of Si rectifiers by more than one order of magnitude. The specific on-resistance increased with temperature according to $T^{2.0}$ dependence. The diodes were capable of operating at temperatures as high as 400℃. The present study demonstrates much potential of SiC for excellent power rectifiers.

1. Introduction

Silicon carbide (SiC) has been received much attention as a hopeful semiconductor material, owing to its wide bandgap, high breakdown field, and high electron saturation drift velocity. Expected applications of SiC are advanced power devices and electronic devices operating at high temperatures where Si or GaAs can not be used. In spite of these outstanding features, the difficulty in crystal growth has delayed the development of SiC devices. However, through efforts in bulk crystal growth, 6H-SiC (bandgap=2.93eV at room temperature) wafers of 1 inch diameter are commercially available today. Recently, homoepitaxial growth of high-quality 6H-SiC at low temperatures has been achieved by "step-controlled epitaxy " utilizing off-oriented 6H-SiC {0001} substrates [1,2]. This breakthrough has brought about the development of high voltage p-n junction diodes [3], Schottky barrier diodes [4], blue light-emitting diodes [5], and high-temperature field effect transistors [6].

As an application to power devices, it has been predicted that SiC devices could replace the entire spectrum of the present day Si-based power devices [7]. In high-frequency power circuits, Schottky barrier diodes are superior rectifiers because of its low turn-on voltage and fast reverse recovery characteristics. However, Si Schottky barrier diodes with blocking voltages over 100V have serious disadvantages of large reverse leakage current and high on-resistances. Although p-i-n diodes have been used for these applications, they show slow switching characteristics.

In this paper , we report Schottky barrier diodes using Au/6H-SiC epilayers with high blocking voltages over 1000V. The dependences of on-resistance on the blocking voltage and temperature are experimentally investigated for the first time.

2. Experimental

Single crystalline N-type 6H-SiC (000$\bar{1}$) C faces grown by an Acheson method were used as substrates. The off-orientation was 5° toward <11$\bar{2}$0>, which was introduced by angle-lapping of the {0001} basal planes. The typical resistivity of substrates was 0.1~0.2Ωcm. N-type 6H-SiC layers were homoepitaxially grown by atmospheric pressure chemical vapor deposition (CVD) in a horizontal reaction tube. The details of " step-controlled epitaxy "has been described elsewhere [1,8]. SiH_4, C_3H_8, and H_2 were used as source and carrier gases. A graphite susceptor was heated by radio frequency (RF) induction. The growth temperature and growth rate were 1500℃ and 2.4μm/h, respectively. The carrier concentration was controlled by in-situ doping with nitrogen using N_2 gas.

For the fabrication of Schottky barrier diodes, Ni was evaporated on the back of substrates, and annealed in a vacuum at 1200℃ to form ohmic contacts. Au Schottky contacts were thermally evaporated on the epilayer through a mask at room temperature. Before Au deposition, the as-grown surfaces were cleaned in organic solvents, heated K_2CO_3, aqua regia, HF, and rinsed in deionized water. The size of circular Au Schottky contacts was 120μm in diameter. I-V and C-V measurements were carried out in air between room temperature and 400℃.

3. Results and discussion

The donor concentration of epilayers obtained from C-V measurements can be controlled in the range of 3.0×10^{15}cm^{-3} to 2.0×10^{18}cm^{-3} by nitrogen doping. Figure 1 shows the dependence of breakdown field (E_b) on doping concentration. Open circles indicate the E_b's in this study. Dashed and solid curves show the E_b's for Si [9] and those estimated from SiC p-n junction

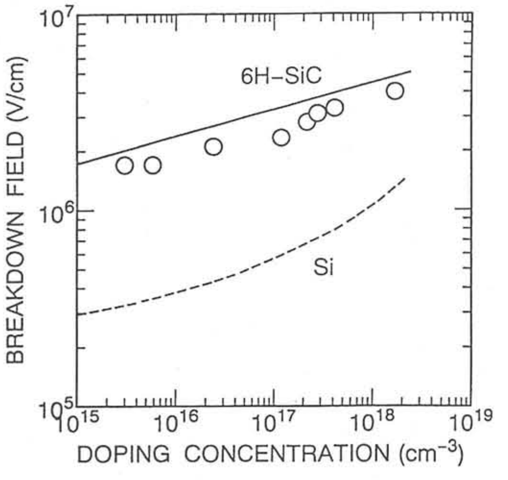

Fig.1. Dependence of breakdown field on doping concentration. Open circles indicate E_b's obtained in this study.

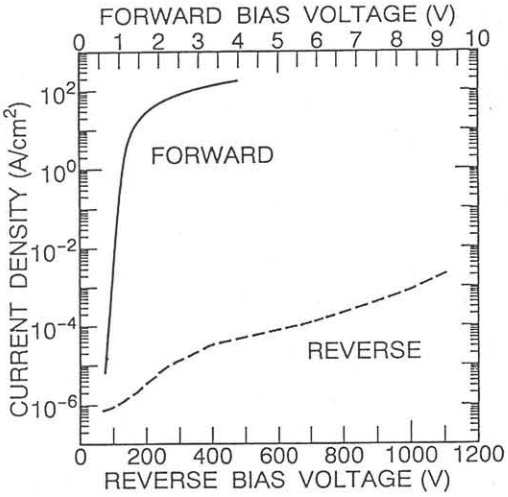

Fig.2. I-V characteristics of a 6H-SiC Schottky barrier diode at room temperature.

characteristics [10], respectively. SiC has much higher E_b's ($1.7\sim4.0\times10^6$V/cm) than Si, which is the most important property for power-device application. Although the E_b's obtained in this study is a little lower than those for SiC p-n junctions, the difference may be attributed to concentrated electric field at the Schottky contact peripheries [9].

Figure 2 shows the I-V characteristics of a typical SiC Schottky barrier diode using an epilayer with a donor concentration of 5.8×10^{15}cm^{-3}. Under the forward bias condition, small ideality factors (n) of 1.1~1.4 were obtained, which indicates that thermionic emission current is dominant. A high current density of 42A/cm^2 was achieved at only 2V as forward bias. The diode showed a high breakdown voltage over 1100V, which is the highest breakdown voltage ever reported for SiC Schottky barrier diodes [4]. The leakage current density was quite low, 4.0×10^{-6}A/cm^2 at -200V and 2.1×10^{-3}A/cm^2 at -1100V, respectively, in spite of no passivation structures. These current densities are lower by orders of magnitude than those previously reported [4]. Note that the thickness of drift region sustaining a blocking voltage of 1100V is only 9.6μm for SiC, which is much thinner than that for Si p-i-n diodes (>90μm) with the same blocking voltage.

In power rectifiers, the on-resistances which limit the current-handling capability become a key characteristic. Figure 3 shows the specific on-resistance (R_{on}) versus breakdown voltage (V_B). Open circles indicate the R_{on}'s obtained in the present study. Solid and dashed lines show the theoretical limits for SiC and Si. The theoretical R_{on}'s are given by

$$R_{on}=R_{on}(\mathrm{epi})+R_{on}(\mathrm{sub}) = \varrho_{epi}W_{epi}+\varrho_{sub}W_{sub}, \quad (1)$$

where R_{on}(epi) and R_{on}(sub) are the resistance for unit area of the epilayer and substrate, ϱ_{epi} and ϱ_{sub} the epilayer and substrate resistivities, W_{epi} and W_{sub} the thicknesses of the epilayer and substrate, respectively. Here, the contact resistance was ignored due to the low value compared with R_{on}(epi) and R_{on}(sub). For SiC, ϱ_{sub} and W_{sub} were assumed as 0.02Ωcm and 300μm, which are commercially available values. Using the breakdown field and mobility (μ) data[9,10], R_{on}(epi) can be calculated using the following equation [13]

$$R_{on}(\mathrm{epi})=4V_B^{\,2}/(\varepsilon E_b^{\,3}\mu), \quad (2)$$

where ε is the permittivity ($\varepsilon_{SiC}=9.7\,\varepsilon_0$). For SiC, the carrier concentration dependence of electron mobility is known [11]. However, Lomakina reported that the mobilities parallel to the c-axis are about one third of these perpendicular to the axis [12]. Therefore, Fig. 3 shows two curves for R_{on} of SiC diodes calculated with and without the consideration on the mobility anisotropy. R_{on}(epi) for Si can be calculated by [7]

$$R_{on}^{\,Si}(\mathrm{epi})=5.93\times10^{-9}V_B^{\,2.5}, \quad (3)$$

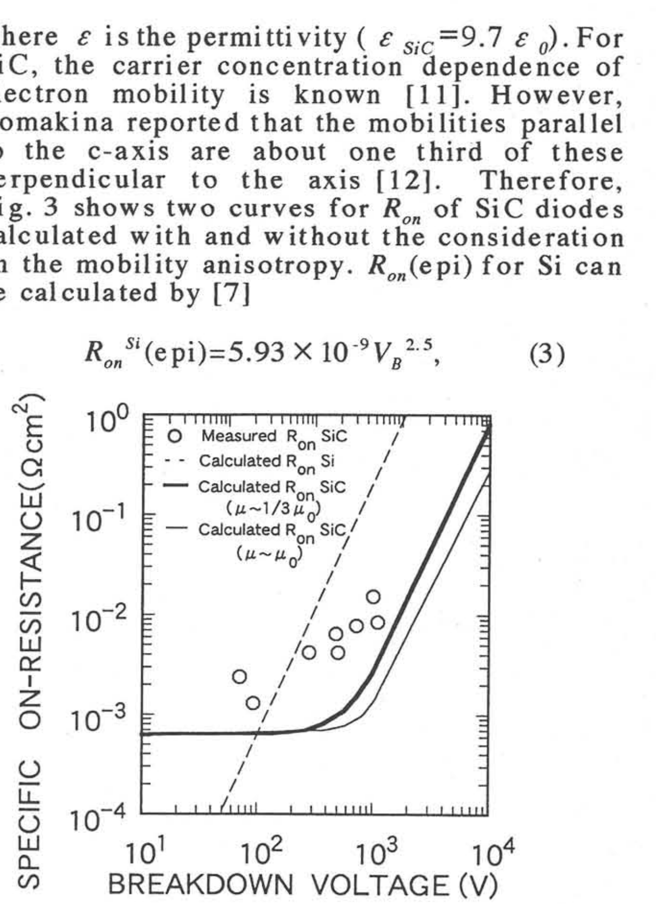

Fig.3. Specific on-resistance versus breakdown voltage.

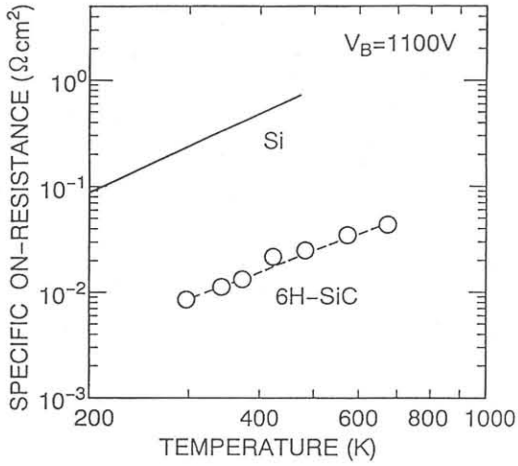

Fig.4. Temperature dependence on specific on-resistance.

R_{on}(epi) becomes dominant for high-voltage devices, because reduced doping concentrations and increased depletion widths are needed to sustain the higher blocking voltages.

The experimentally obtained specific on-resistances for SiC rectifiers with breakdown voltages of 500~1100V are lower than the theoretical limits of Si rectifiers by one order of magnitude. For example, R_{on} is only $8.5\times10^{-3}\Omega cm^2$ for 1100V SiC rectifiers. Relatively higher R_{on}'s were obtained for the low-voltage SiC rectifiers, which may be ascribed to the high substrate resistances in this study ($>10^{-3}\Omega cm^2$). By the optimization of device structures, further improvement of R_{on} is expected.

Figure 4 shows the temperature dependence of R_{on} for a 1100V Schottky barrier diode between room temperature and 400℃. Open circles represent the R_{on}'s for a SiC rectifier obtained in the present study. The solid curve shows the theoretical values for a Si Schottky rectifier with the same blocking voltage, calculated using mobility data [14]. The R_{on}'s increase monotonously with temperature, which is an essential characteristic to avoid thermal runaway. The slopes of the plots for Si and SiC are 2.4 and 2.0, respectively. The increase in R_{on} for Si is caused by the decrease in electron mobility which follows $T^{-2.4}$ dependence [14]. Although SiC has the temperature dependence of electron mobility quite similar to Si [15], the carrier concentration increases with temperature, because N donors are not fully activated at room temperature. This may be the reason why the slope of the R_{on} versus temperature plot is smaller in SiC. It should be noted that SiC Schottky barrier diodes can operate with low-R_{on}'s at temperatures as high as 400℃. This result shows that high-temperature tolerant power devices can be developed using SiC.

4. Conclusion

Au/6H-SiC Schottky barrier diodes were fabricated using layers homoepitaxially grown on 6H-SiC substrates by step-controlled epitaxy. High breakdown fields of $1.7\sim4.0\times10^6$V/cm (the donor concentration = $3.0\times10^{15}cm^{-3}\sim2.0\times10^{18}cm^{-3}$) were obtained from the diode characteristics. A breakdown voltage over 1100V could be achieved, which is the highest ever reported for SiC Schottky barrier diodes. These high-voltage SiC rectifiers had low specific on-resistances lower than the theoretical limits of Si rectifiers by more than one order of magnitude. The specific on-resistance increased with temperature according to $T^{2.0}$ dependence. The diodes were capable of operating at temperatures as high as 400℃. The present study demonstrates much potential of SiC for excellent power rectifiers.

Acknowledgment

This work was partially supported by a Grant-in-Aid for Scientific Research from Ministry of Education, Science and Culture of Japan.

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