Extended Abstracts of the 18th (1986 International) Conference on Solid State Devices and Materials, Tokyo, 1986, pp. 101-104

B-3-4

High-Temperature Characteristics of CVD-Grown β-SiC p-n Junction Diodes

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β-SiC p-n junction diodes with a mesa structure are fabricated using chemical vapor deposition on Si substrates with an impurity doping during the growth. Current-voltage and capacitance-voltage characteristics of the diodes are measured at high temperatures up to 500 °C. No significant degradation of the characteristics during the high-temperature operation occurs even at 500 °C. But the rectification becomes poor at high temperatures, with an increase in reverse leakage current and an decrease in built-in potential.

§1. Introduction

Since silicon carbide (SiC) has a large band gap and excellent thermal and chemical stabilities, it is a prime candidate material for high-temperature and high-power electronic devices. Moreover, the large values of saturation electron drift velocity (2×10^7 cm/sec), breakdown electric field (5×10^6 V/cm), and thermal conductivity (5 W/cm °C) of SiC[1)] are quite favorable for high-temperature and high-power operations of the devices. However, the development of SiC device technology has been hampered by the lack of a reproducible process for obtaining large-area single crystals.

Recently, a new technique of chemical vapor deposition (CVD) has been developed for the hetero-epitaxy of SiC, and large-area single crystal films (2-inches diameter) of cubic SiC (β-SiC) have been reproducibly obtained on Si substrates.[2-7)] The authors succeeded in growing high-quality epitaxial films with low electron concentrations ($\sim 3 \times 10^{16}$ cm^{-3}) and high electron mobilities (~ 510 cm^2/Vsec)[7)]. Schottky barrier diodes,[8)] p-n junction diodes[6)], and MOS structures[9)] have been fabricated by several researchers. However, electrical characteristics at high temperatures of these device structures have not yet been studied in detail.

In the present paper, p-n junction diodes are fabricated using CVD growth on Si substrates with an impurity doping during crystal growth. Diode characteristics are improved by the refinement of fabrication processes, and current-voltage and capacitance-voltage characteristics are measured at high temperatures. The experimental results and the crystal quality of the epitaxial films are discussed from the viewpoint of a high-temperature device material.

§2. Fabrication Procedures

2-1 CVD growth

Single crystal films of β-SiC are epitaxially grown on Si substrates by CVD using SiH_4 and C_3H_8 source gases and a H_2 carrier gas. A horizontal water-cooled quartz tube with an inside diameter of 120 mm is used as a reaction chamber. A 2-inches wafer of n-type Si(100) single crystal is placed on a SiC-coated graphite susceptor in the reaction chamber. The susceptor is heated by rf induction, and the temperature of the substrate is measured with an optical pyrometer.

Prior to CVD growth, the substrate surface is etched with a HCl gas at about 1100 °C. After the etching, C_3H_8 gas is introduced into the reaction chamber and the substrate is heated at around 1350 °C for 1-2 min in order to form a very thin carbonized "buffer" layer to minimize the effects of lattice mismatch and thermal-coefficient difference between SiC and Si. Subsequently, SiH_4 and C_3H_8 are introduced into the chamber with H_2 carrier gas. The flow rates are 2 SCCM, 2 SCCM, and 10 SLM,

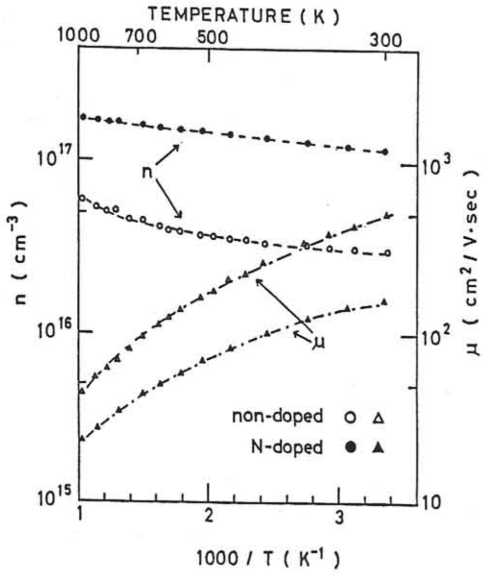

Fig. 1. Electrical properties at high temperatures of non-doped and nitrogen-doped n-type β-SiC films.

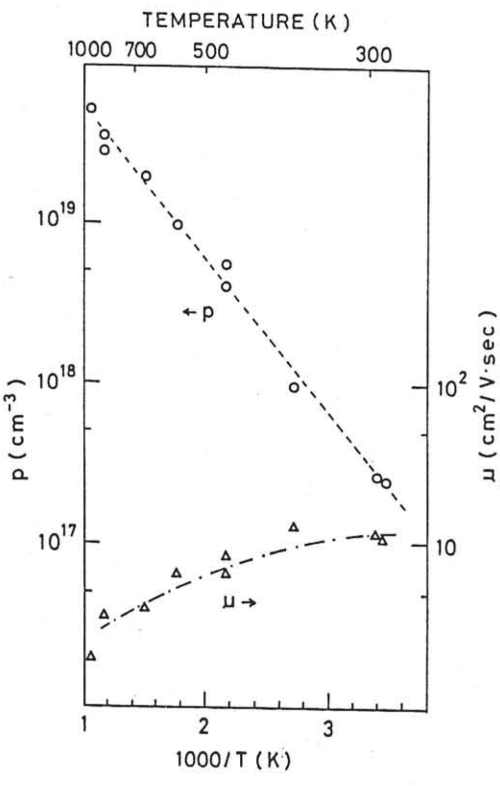

Fig. 2. Electrical properties at high temperatures of aluminum-doped p-type β-SiC film.

respectively. A single crystal film with a mirror-like surface is epitaxially grown at 1300-1350 °C with a growth rate of about 3 μm/h.

Non-doped films show n-type conduction. Nitrogen-doped n-type films and aluminum-doped p-type films are obtained by adding nitrogen gas and trimethylaluminum gas to the source gases. Figures 1 and 2 show carrier concentrations and Hall-mobilities of typical non-doped n-type, nitrogen-doped n-type, and aluminum-doped p-type films (the film thicknesses are 8-10 μm).

2-2 Diode fabrication

The fabrication process of p-n junction diodes is as follows: Non-doped n-type layer is grown on n-type Si substrate (ρ = 0.01 Ωcm). Then, aluminum-doped p-type layer is successively grown on the n-layer. The flow rate of trimethylaluminum is 0.12 SCCM. The thickness of each layer is about 3 μm. Carrier concentrations of the n- and p-layers by Hall measurements are approximately 1×10^{17} and 2×10^{17} cm^{-3}, respectively.

Mesa-structure diodes are fabricated using the reactive ion etching with CF_4 and O_2 gases. Masks for the etching are aluminum metals. The depth of mesa etching is approximately 4 μm. Then, ohmic electrodes for the p-layer and the Si substrate are formed. Each diode is cut off with a diamond dicing blade and mounted on a diode stem. The junction area is 3.1×10^{-2} mm^2. The heterojunction between the n-layer and the Si substrate was confirmed to have ohmic characteristics with low resistance.

§3. Diode Characteristics

Figure 3 shows current-voltage (I-V) characteristics of a typical diode up to 500 °C. All the diodes fabricated from the same growth run have similar characteristics. The characteristics show no significant degradation during the operation

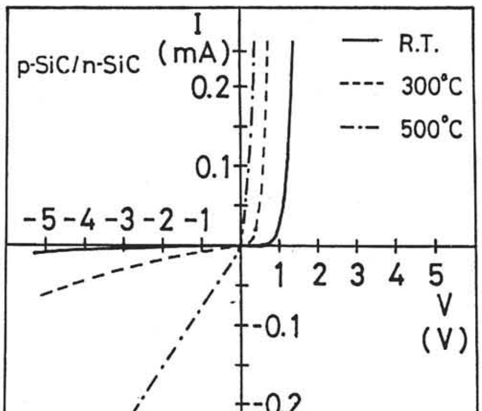

Fig. 3. Current-voltage characteristics at high temperatures of a typical p-n junction diode.

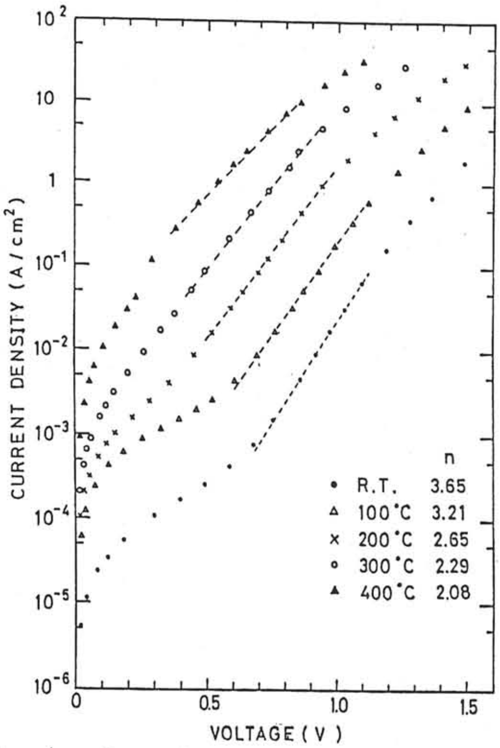

Fig. 4. Forward current-voltage characteristics at high temperatures plotted on a semilogarithmic scale.

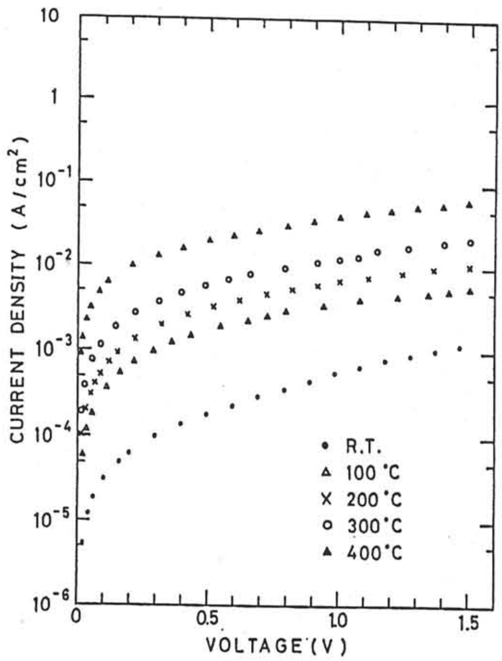

Fig. 5. Reverse current-voltage characteristics at high temperautres plotted on a semilogarithmic scale.

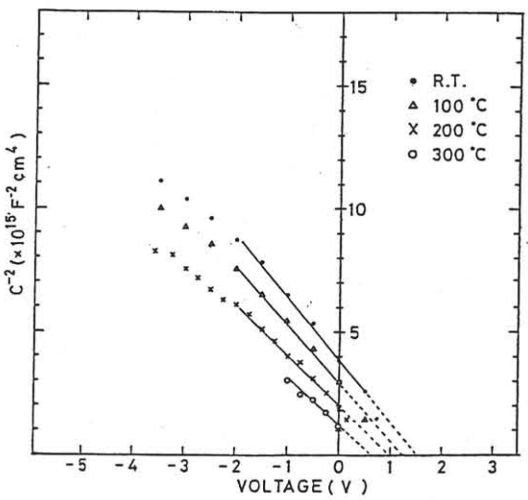

Fig. 6. Capacitance-voltage characteristics as C^{-2} vs. V at high temperatures.

even at 500 °C. At room temperature, relatively good rectification is observed, with a forward turn-on voltage of around 1.2 V and a reverse leakage current of 5 μA at 5 V. But the rectification becomes remarkably poor with temperature as in Fig. 3.

Semilogarithmic plots of the forward and reverse I-V characteristics up to around 1.5 V at high temperatures are shown in Figs. 4 and 5. As generally seen for practical p-n junction diodes, there are three regions in the forward characteristics. At room temperature, for example, excess currents at applied voltages lower than about 0.6 V, exponentially increasing currents at 0.6-1.1 V, and gradually increasing currents at higher than 1.1 V are observed. Values of the n factor (I~exp (qV/nkT)) in the exponential current region at high temperatures are shown in Fig. 4, although the region is rather narrow. The value is 3.7 at room temperature and decreases with temperature down to 2.1 at 400 °C. Reverse currents shown Fig. 5 increase gradually with applied voltage. The magnitudes of current at low reverse applied voltages are almost the same with those at low forward voltages.

Capacitance-voltage (C-V) characteristics of the diodes are measured at 1 kHz, and shown as C^{-2} vs. V in Fig. 6. Each C^{-2} vs. V cannot be expressed by a straight line, but from the intercept of a partially straight region at C^{-2} = 0, the built-in potential is obtained as in Fig. 6. The value at room temperature is 1.5 V, and decreases with temperature, down to 0.6 V at 300 °C.

§4. Discussion

SiC is expected to be a potential material for high-temperature and high-power electronic devices. Figure 7 shows calculated temperature dependences of the band gap and the intrinsic car-

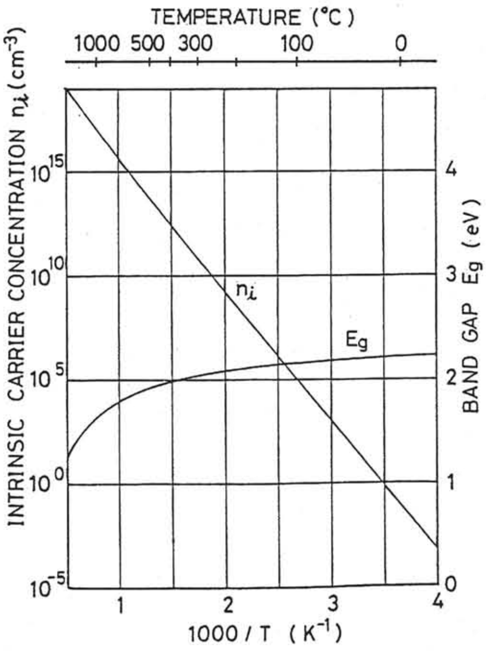

Fig. 7. Calculated temperature dependences of the band gap and the intrinsic carrier concentration of β-SiC.

rier concentration of β-SiC[10]. Owing to the large band gap, the intrinsic carrier concentration is as low as 10^{14} cm^{-3} even at 500 °C. As in Fig. 1, the carrier concentration of non-doped n-type film of CVD-grown β-SiC is low enough even at 700 °C (973 K). N-type conduction can be controlled by nitrogen doping as in Fig. 1. The ionization energy of nitrogen donors was found to be 34-37 meV[7]. On the other hand, aluminum acceptors have rather large ionization energy (about 200 meV from the slope of the broken line in Fig. 2), and the hole concentration of aluminum-doped p-type film varies rapidly with temperature. To attain a sufficient hole concentration at room temperature, a large amount of aluminum acceptors has to be doped in. This probably causes deterioration in crystal quality of p-type films as well as out-diffusion of aluminum atoms into the adjacent n-type film, mainly through lattice defects of the film.

The result that no significant degradation of the diode characteristics was observed during the operation even at 500 °C proves the excellent stability of β-SiC at high temperatures. But the characteristics obtained by the present study are rather different from those of ideal p-n junction diodes. Reverse saturation currents estimated for an ideal abrupt junction diode of β-SiC are as small as 2×10^{-7} A/cm^2 at 400 °C, but the experimental results show much larger values of 1×10^{-3} A/cm^2 even at room temperature and 7×10^{-2} A/cm^2 at 400 °C at a reverse voltage of 1.5 V. A large amount of excess currents are observed at low applied voltages in the forward characteristics, and the values of the n factor are as large as 2.1-3.7. The built-in potentials obtained from the C-V measurements are 1.5 V at room temperature and 0.6 V at 300 °C, which are smaller than 1.9 V and 1.6 V, respectively, from the estimation for an ideal diode having the same carrier concentrations with the measured diode.

Recent studies[7, 11] on CVD-grown β-SiC on Si substrates have revealed the presence of crystal imperfections such as dislocations and stacking faults as well as non-stoichiometric defects or impurities. Diffusion of doped impurities through the imperfections and charge traps in the junction region due to the defects and impurities probably affect the diode characteristics. Suppressing the generation of crystal imperfections and defects in the epitaxial film and refining the impurity doping technique, it can be expected that the diode characteristics will be much improved.

§5. Conclusions

I-V and C-V characteristics of CVD-grown p-n junction diodes of β-SiC have been measured at high temperatures up to 500 °C. The rectification characteristics become poor at high temperatures, with an increase in reverse leakage current and an decrease in built-in potential. But the characteristics show no significant degradation during the operation even at 500 °C.

The diode characteristics will be much improved with high-quality epitaxial films free from crystal imperfections and defects.

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