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Characterization of Schottky diodes on 4H-SiC with various off-axis angles grown by sublimation epitaxy

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Abstract. The effects of basal-plane defects on the performance of 4H-SiC Schottky diodes using a Ni electrode are demonstrated. Systematic characterization was performed using 4H-SiC epitaxial layers grown by sublimation epitaxy on substrates with various off-axis angles. As the off-axis angle increases, the ideality factor of the current-voltage characteristics increases, and the Schottky barrier height decreases, corresponding to an increase in the number of basal-plane defects. The reverse-bias current degrades for high off-axis samples. These results indicate that basal-plane defects degrade the device performance. Schottky diodes that possesses good characteristics were obtained for samples with low off-axis angles (2^o- and 4^o-off samples).

Introduction

4H-SiC is a promising semiconductor material for high-power device applications because of its physical characteristics, such as a high breakdown field and high thermal conductivity. A 4H-SiC homo-epitaxial layer is usually grown on a (0001)-oriented substrate with an off-axis angle of 8^o to control the polytype. If stacking faults (SF) or basal plane dislocations (BPD) are laid on the substrate with an off-axis angle, the basal-plane defects propagates from the substrate into the epitaxial layer. This results in the degradation of the device performance. It has been reported that stacking faults lowers the Schottky barrier height [1].

In this study, current(I)-voltage(V) characteristics of Schottky diodes including various numbers of basal-plane defects, are systematically studied to clarify the influence of the basal-plane defects on diode characteristics. A series of SiC substrates sliced from a single SiC ingot, having an appropriate density of basal-plane defects, was used for epitaxial growth. Accordingly, the number of basal plane defects in the Schottky diodes varied from 0 to 20 by varying the off-axis angle of the substrate. The ideality factor (n), barrier height, and reverse-bias current of the Schottky diodes were examined as a function of the number of basal-plane defects.

Sample Preparation

4H-SiC substrates with off-axis angles of 2^o, 4^o, 6^o, and 8^o toward $<11\bar{2}0>$ were prepared by slicing them from a single 4H-SiC ingot, as shown in Figure 1. Epitaxial growth on these substrates was carried out by sublimation epitaxy [2] in which the distance between the substrate and the source was set at 1.0 mm. A purified SiC source, with an impurity concentration of less than 10^{17} cm^{-3}, and a high-purity graphite crucible were employed to purify the epitaxial layers [3]. A tantalum sheet was placed in the graphite crucible to prevent graphitization of the source and to maintain a constant growth rate during the growth process [4]. The graphite crucible was inductively heated by a ratio-frequency generator operating at 20 kHz. During the crystal growth process, the temperature at the bottom face of the crucible was maintained at 1900°C under a

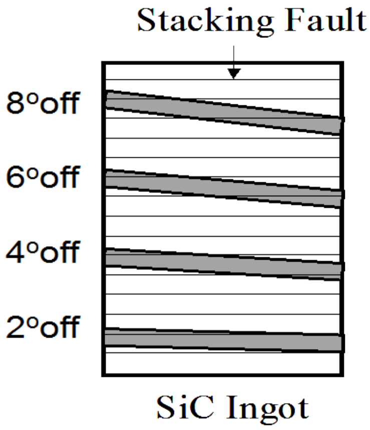
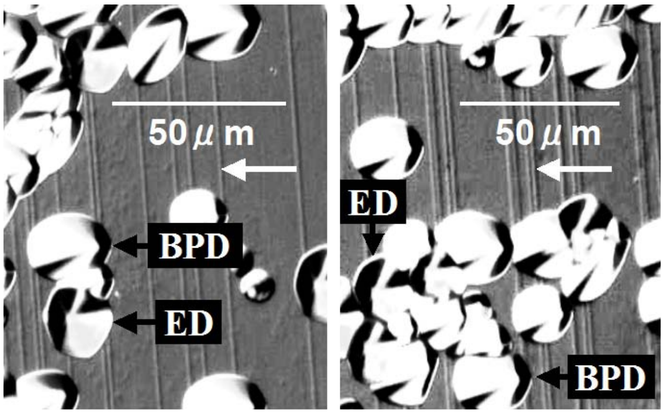


Figure 1 Schematic cross section of the substrate used in this study.



(a) (b)

Figure 2 Micrograph of the substrate (a) and epitaxial layer (b) after KOH etching.

constant argon pressure of 4.5 Pa.

The thickness and growth time were maintained at approximately 32 μm and 1 h, respectively. The polytype of the epitaxial layer was confirmed to be 4H-SiC by Raman scattering spectroscopy. Stacking fault density (SFD) and basal plane dislocation density (BPDD) in the epitaxial layers were evaluated by counting the etch-pit density, formed by molten KOH etching (500°C and 1min). To confirm the propagation of basal-plane defects during epitaxial growth, a pair of adjacent substrates was sliced from the ingot. One was used for KOH etching, and the other for homo-epitaxy, followed by KOH etching.

Figure 2(a) and (b) show micrographs of the substrate and epitaxial layer after KOH etching, respectively. Lines indicated by white arrows are identified as SFs. The BPDD and edge dislocation density (EDD) were evaluated by counting the etch pits formed by basal plane dislocations (BPD) and edge dislocations (ED). As shown in Fig. 3, SFD and BPDD increase with the off-axis angle. An increase in the off-axis angle causes an increase in substrate defect densities because the defects exist on the c-plane, and the substrates were cut from the same part of the identical ingot. However, EDD is independent of the off-axis angle and remains constant. The SFD and BPDD of the epitaxial layer are approximately equal to those of the substrate. Therefore, SFs and BPDs that are laid on the substrate propagate into the epitaxial layer. The number of basal-plane defects in the epitaxial layer was controlled by varying the off-axis angle of the substrate.

Nickel was employed for both ohmic and Schottky contacts. The ohmic contact was formed by annealing nickel at a temperature of 1000°C in Ar under atmospheric pressure for 1 min. The Schottky contact, with a diameter of 100 μm, was formed by photolithography. Considering the SFD and BPDD in Fig. 3, and the diameter of the electrode (100 μm), the Schottky contacts contain SFs of 0–4, 5–7, 7–11, and 9–11 for 2°-, 4°-, 6°-, and 8°-off samples, respectively. The BPDs are estimated to be 2–5, 4–7, 7–11, and 8–18 for 2°-, 4°-, 6°-, and 8°-off samples,

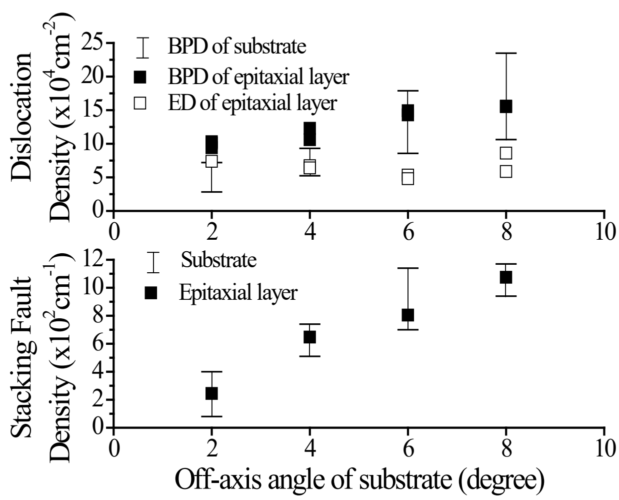


Figure 3 Dependence of the SFD and BPDD on the off-axis angle of the substrate.

respectively. Each sample has 50 electrodes. The lowest space charge density of homo-epitaxial layers was determined to be as low as 5×10^{16} cm^{-3} from the capacitance-voltage characteristics of the Schottky diodes. The Schottky diodes in the following figures exhibit a space charge density of 1–2 $\times 10^{18}$ cm^{-3}.

Current-Voltage Characteristics

Figure 4 shows examples of Schottky diodes at various off-axis angles. Although approximately 10% of the diodes exhibit non-ideal characteristics with two Schottky diodes having two barrier heights in parallel, the remaining 90% of the diodes exhibit single barrier characteristics with a barrier height larger than 1 eV. The *I-V* curve of the Schottky diodes that possess single barrier characteristics shifts to a low voltage with an increase in the off-axis angle (Fig. 4), implying a lowering of the barrier height of the sample with a large off-axis angle. The reverse-bias current increases with the off-axis angle.

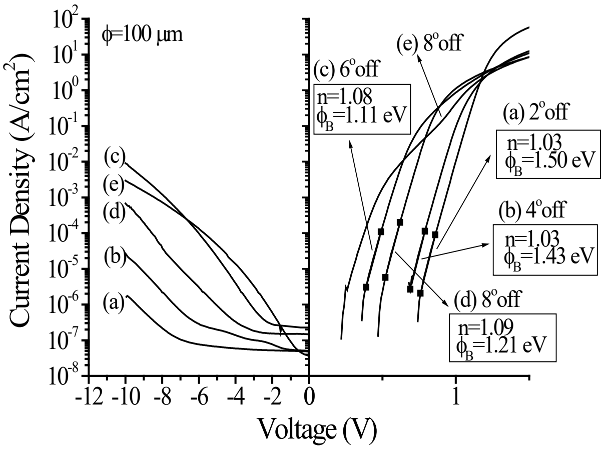


Figure 4 Typical I-V characteristics of Schottky diodes.

The previous study examined the origin of non-ideal diodes with two barrier heights with respect to deep-level defects [5], and revealed a correlation between deep level defects and barrier heights ranging between 0.6 and 1.05 eV. In this study, among all the off-axis samples, non-ideal characteristics were observed most frequently for 8°-off samples containing the largest SFD and BPDD. It was observed that the existence of deep levels, with respect to SFs or BPDs, lowered the Schottky barrier height. Next, we focus on Schottky diodes with single barrier characteristics.

Figure 5 shows the dependence of the barrier height on the off-axis angle of the substrate for diodes with single barrier characteristics. The barrier height was determined from the forward *I-V* characteristics. The barrier height decreases as the off-axis angle of the substrate increases. For example, the average value of the barrier height for 8°-off samples is lower than that of 2°-off samples by ~0.2 eV. In addition to lowering the barrier height, the barrier height distribution for 6°- and 8°-off samples becomes broader than for 2°- and 4°-off samples. Since SFD and BPDD increase with the off-axis angle of the substrate, these basal-plane defects and other relevant defects degrade the barrier height.

Figure 6 shows the dependence of the ideality factor on the off-axis angle of the substrate for diodes with single barrier characteristics. The most frequent value of the ideality factor increases with the off-axis angle. While distributions of the ideality factor for the 2° and 4°-off samples are very similar, distribution of the high angle (6° and 8°-off) samples clearly becomes broader than that of low off-axis angle (2° and 4°-off) samples. These tendencies are similar to the distribution of the barrier height.

For Schottky diodes with single barrier characteristics, the barrier height derived from the *I-V* characteristics showed a good correlation to the ideality factor on the basis of the statistical data from ~200 diodes (not shown here). The ideality factor improved as the barrier height increased. The ideal barrier height was estimated to be 1.55 eV, by extrapolation of the correlation to $n = 1$. This value is close to the reported ideal value of 1.60 eV [6].

The reverse-bias current at 10 V increases with the off-axis angle, as shown in Fig. 7. Distribution of the reverse current for the 8°-off samples clearly becomes broader than for those with low off-axis angles. Based on these results, it can be stated that the reverse-bias current degrades with an increase in the off-axis angle, corresponding to an increase in the basal-plane defects. The previous study reported that SFs had a significant influence on the leakage current [7]. The basal-plane and other relevant defects cause degradation of the reverse-bias current.

The EDD value remains nearly constant, regardless of the off-axis angle, as shown Fig.3. However, the barrier height, ideality factor, and reverse-bias current degrade with an increasing off-axis angle. Therefore, ED does not significantly degrade the Schottky diode characteristics.

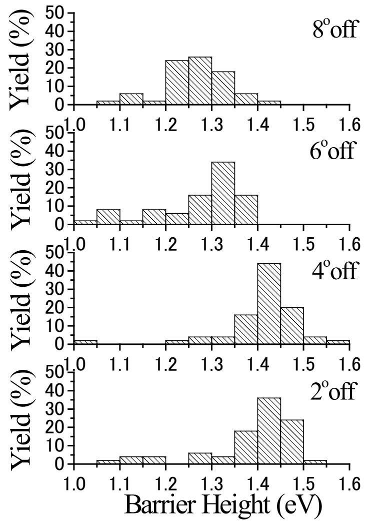


Figure 5 Dependence of Schottky barrier height on the off-axis angle of the substrate

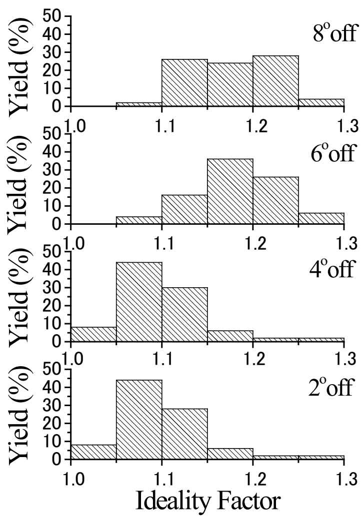


Figure 6 Dependence of ideality factor on the off-axis angle of the substrate

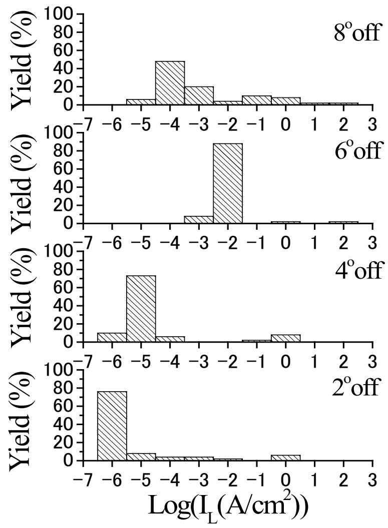


Figure 7 Dependence of reverse-bias current density at 10 V on the off-axis of the substrate

Conclusion

4H-SiC Schottky diodes with 2°–8°off-axis angles were fabricated. A series of SiC substrates, sliced from a single SiC ingot were used for epitaxial growth. Accordingly, the number of basal-plane defects in the Schottky diode (100 μm in diameter) varied in the range between 0 and 20 by varying the off-axis angle of the substrate. As the off-axis angle increases, the ideality factor of the current-voltage characteristics increases, and the barrier height derived from current-voltage characteristics decreases. The reverse-bias current degrades for high off-axis samples. In addition, distributions of the barrier height and reverse-bias current for 8°-off samples become broader than for 2°- and 4°-off samples. Because the number of stacking faults and basal plane dislocations in a diode increases with the off-axis angle of the substrate, these basal-plane and other relevant defects degrade the barrier height, ideality factor, and reverse-bias current.

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