EBIC study of dislocations and stacking faults in 4H-SiC homoepitaxial films

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Abstract

The electrical properties of dislocations and stacking faults in 4H-SiC homoepitaxial films with 8˚ off from the (0001) Si surface were investigated by using electron-beam-induced current (EBIC) technique. First, four different dislocations, namely basal plane, screw, edge-I and edge-II dislocations, were revealed by molten KOH etching. EBIC observation shows the electrical activity of basal plane dislocation (BPD) is the strongest and becomes weaker in this order. Moreover, it is found that, under the electron beam irradiation, the BPDs dissociates into two partials with stacking faults between them. In the EBIC image, stacking faults were seen as a bright area, which is peculiar to this material. The mechanism of this bright contrast was discussed in terms of the energy state of stacking faults.

1. Introduction

SiC is a promising wide-bandgap semiconductor for high-power devices of ultra-low loss, high frequency, and high temperature operation. Due to the advancement of crystal growth technology, high-quality 4H-SiC wafers are available now. By using the homoepitaxial growth of 4H-SiC layer, we can obtain micropipe-free SiC films for electronic devices. After the elimination of micropipes, the next harmful defects are dislocations. In the case of 4H-SiC p-n diode, Neudeck et al. [1] showed that there were 5~35% reduction in breakdown voltage if the device contains one screw dislocation. Wahab et al. [2] reported that the serious reduction of breakdown voltage in 4H-SiC Schottky diode was caused by high density of screw dislocations. According to our observations in epitaxially grown 4H-SiC films, the dominant dislocations are basal plane dislocations (BPDs). However, only few researchers pay particular attention to these dislocations.

Furthermore, it has been found recently that 4H-SiC bipolar devices show a considerable degradation under forward bias operation. This is caused by the formation and development of stacking faults (SFs) in the active region of SiC bipolar devices [3]. BPD is generally considered as one of the nuclelation sites of SFs. Due to the low SF energy of 4H-SiC in the basal plane (~15 mJ/m² [4], compared with Si ~55 mJ/m² [5]), BPDs are easily dissociated into partial dislocations with SFs in between. Following the work of Twigg et al. [6], the mobile segments have a Si(g) core whereas the immobile segments have a C(g) core. The continuous movement of Si(g) partials results in the expansion of SFs. In the homoepitaxial 4H-SiC films, it is found that the formation of SFs is caused by the dissociation of BPDs, while the subsequent development of SFs is due to the glide of partials. Thus, the understanding of both BPDs and SFs is necessary for the further improvement of 4H-SiC devices.

In this work, the electrical activities of dislocations and SFs in 4H-SiC homoepitaxial films were studied by using electron-beam-induced current (EBIC) method. The bright SF in EBIC image was discussed according to its quantum-well state.
2 Experimental

6 μm thick 4H-SiC epitaxial film doped with N to $1.8 \times 10^{16}$ cm$^{-3}$ was grown on an off-cut 4H-SiC (0001) Si-face substrate oriented $8^\circ$ toward the $\langle 11\overline{2}0 \rangle$ direction by chemical vapour deposition (CVD). After the growth, a Schottky contact (Ni, 10 nm thick) and Ohmic contact (Al, 200 nm thick) were deposited on the frontside and backside, respectively. Dislocations in the epilayer were observed by EBIC mode of a scanning electron microscope (Hitachi S4200-SE). The schematic representation of the EBIC measurement was shown in Figure 1. The accelerating voltage and electron-beam current were 20 kV and 0.8 nA, respectively. The temperature of observation was varied from 50 to 300 K using the specimen cooling system flowing liquid helium gas [7]. EBIC contrast of a defect is defined by,

$$C_{EBIC} = \frac{I_0 - I_d}{I_0} \times 100 \quad (\%)$$

where $I_0$ and $I_d$ are the EBIC currents at the background and at dislocations, respectively.

3 Results and discussion

Figure 2 shows an EBIC image at 300K (a) of the 4H-SiC epilayer and an optical micrograph (b) of the same region after KOH etching. In Fig. 2(a), there appear some dark lines and dots distributed randomly. The dark lines (marked “D”) are aligned along $\langle 11\overline{2}0 \rangle$ direction, their EBIC contrasts gradually increase from left (~6%) to right (~18%) and then decrease a little (~16%). The dark dots marked with “A”, “B” and “C” show different EBIC contrasts, which are about 12%, 10% and 8%, respectively. This indicates that their types may differ. Etch pits in Fig. 2(b) have different shapes and sizes, and they are located exactly at the same positions as dark lines and dots observed in the EBIC image. According to the previous paper [8], the coincidence allows us to identify four kinds of dislocations due to the morphology of etch pits. The oval etch pits are related to basal plane dislocations, which correspond to the dark lines in the EBIC image. Large and dark etch pits with a bright spot in the center are related to screw dislocations (“A” mark in Fig. 2a), whereas small-size dark etch pits are associated with edge dislocations (Edge-I, “B” mark). Another kind of small and bright etch pits are also related to an edge type, which is denoted as edge-II (“C” mark) here. The screw and edge dislocations appear as dark dots in the EBIC image, indicating that they are threading dislocations.

The temperature-dependence of EBIC contrasts for various dislocations are shown in Figure 3. For each type, about 25 dislocations were collected to calculate the EBIC contrasts. The EBIC contrasts of BPDs increase from ~12% to ~18% by increasing temperature, reach the maximum at around 250 K, and then decrease slightly to room temperature. The EBIC contrasts of threading dislocations are (8 to 12%) for screw dislocation, (6 to 10%) for edge-I and (6 to 8%) for edge-II dislocations, which show a similar behavior as the temperature increases. At
same temperature, the EBIC contrasts of dislocations are stronger in the order of BPD > screw > edge-I > edge-II. As discussed in the previous publications [9], the increase of EBIC contrast with temperature suggests that the dislocations are accompanied with deep levels. In the case of Si, on the contrary, the EBIC contrasts of clean and straight dislocations are high at 100 K and decrease with increasing temperature, suggesting that they have shallow levels [10]. When these dislocations in Si are contaminated with transition metals (Fe, Cu, et.al), their EBIC contrasts increase with temperature, similar to the uncontaminated SiC [11]. We may attribute the deep levels in SiC to the impurities or special dislocation structures. Since 4H-SiC film is grown at higher temperature than Si, namely 1550 ºC, unintentional contamination may be possible. It has been reported that some trap centers can be produced by the impurities, like V (Ec-0.92 eV) and Ti (Ec-0.17 eV) [12]. Another possibility is the special dislocation structure, i.e., the structure of dislocations may be modified by some intrinsic defects (ex. Z center, located at Ec-0.63 eV [13]).

As it was obtained in Fig.3, BPD has the highest EBIC contrasts, which suggest that BPDs are the most electrically harmful in the 4H-SiC epitaxial films. We then suppose that there exist three possible reasons. One is due to the geometry of the dislocations. Since the inclination angles in respect to the epitaxial surface are different for BPDs and threading dislocations, they may have some impacts on the EBIC contrasts. The special dislocation core structure is another possibility. The cores of BPDs may have more recombination centers, which result in higher EBIC contrasts. The third possibility is impurities gettered at dislocations. Further investigation is on the way to determine which factor is dominant.

Fig. 4 shows the EBIC images at 20 kV illustrating the dissociation of a BPD under electron-beam irradiation (RT). Fig. 4(a) shows the initial state. The single dark line corresponds to a BPD with dislocation line in (0001) plane (8º off with respect to the surface). The BPD intersects the surface at the right end. After 30 min of
electron-beam irradiation, a trapezoid feature was observed in Fig. 4(b). This feature is related to the development of a SF as a result of the BPD dissociating into partial dislocations. One partial stays at the same position as the initial BPD, while the other moves during the irradiation. Following the work of Skowronska et al. [14], the schematic diagram of each partial is shown in the illustration of Fig. 4(b). The moving Si(g) \(30^\circ\) and immobile C(g) \(30^\circ\) partials are connected by a Si(g) \(90^\circ\) partial. The contrast width of C(g) \(30^\circ\) partial is wider than that of Si(g) \(30^\circ\) partial, indicating that C(g) \(30^\circ\) partial has a larger recombination cross-section. It should be pointed out that SF is brighter than the background, which is peculiar to this SF, since electrical active defects generally show dark contrast due to carrier recombination.

![Image](image.png)

**Fig. 4.** EBIC imaging of the dissociation of a BPD under different irradiation time. (a) initial BPD; (b) after 30 min irradiation.

One possible reason for the bright SF is due to the depletion of impurities. However, such effect is less possible because of the following reasons. The impurity gettering is quite difficult in SiC at RT due to the very small impurity diffusion coefficient. Moreover, if Si(g) \(30^\circ\) partial captures electrically active impurities during its motion, its EBIC contrast should change, while it is not the case. Thus, another reason for the bright SF should be proposed.

![Model](model.png)

**Fig. 5.** A model that explains the bright SF in EBIC image at RT.

According to the cathodoluminescence data [15], SF introduces a natural quantum-well state which is 0.25 eV lower than the conduction band edge of 4H-SiC. By this quantum-well state, a model is presented to explain the bright SF, as shown in Figure 5. This schematic is a cross-sectional view of SF during EBIC measurement. Schottky contact is made on the surface to produce a depletion region where the internal electric field exists. In EBIC technique, minority carriers (holes in this case) generated by the impinging beam are collected as EBIC signals by this internal electric field. Before electron-beam irradiation, the electron density in the matrix is \(n_i\) at equilibrium. However, during the irradiation, a number of electron-hole (\(e-h\)) pairs are generated in a pear-shaped volume, with the carrier densities of \(\Delta n\) and \(\Delta p(=\Delta n)\) for electrons and holes, respectively. Hence, at the background region, the total electron density becomes \(n_i + \Delta n\) in the excited volume. While at the SF, considerable fraction of generated electrons is captured by the quantum-well state. Those electrons diffuse away
along the SF, and consequently the electron density in the generation volume decreases to \( n_0 + \Delta n - \zeta n \), where \( \zeta \) is the electron density that diffuses away. Due to this reduction, the hole lifetime in the volume may increase. This increase may be the cause of increase of EBIC current at SF region. The detailed analysis is now going on.

4 Summary

The electrical activity of four types of dislocations in the 4H-SiC homoepitaxial film was investigated by EBIC technique. The EBIC contrasts of dislocations are stronger in the order of BPD > screw > edge-I > edge-II. It should be noted that two types of edge dislocations, which were distinguished by etch pit images, give different EBIC contrasts. The EBIC contrasts of all kinds of dislocations increase with increasing temperature, indicating that the dislocations have deep levels. The dissociation of BPD and creation of SF were also observed. The possible explanation of bright SF contrast was proposed.

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References