Electrical and Optical Properties of Stacking Faults in 4H-SiC Devices

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By using electron-beam-induced current (EBIC) and cathodoluminescence (CL) techniques, we characterized the electrical and optical properties of stacking faults (SFs) in 4H-SiC $p^+/-n$ junctions and compared with those in Schottky diodes. In the EBIC images, SFs penetrating the $p^+/-n$ junction are bright in the n^- region and dark in the p^+ region, while SFs observed in the Schottky diode are only bright. In CL measurements, a characteristic peak (417 nm) appears at SFs in the n^- region, similar to those observed in Schottky diodes. The 417-nm peak, however, does not occur obviously at either the p^+ layer or within the depletion region. The reason for the absence of this emission is discussed in terms of band bending at the junction.

Key words: Stacking fault, 4H-SiC, Al doping, basal plane dislocation, quantum well, dissociation, irradiation

INTRODUCTION

Silicon carbide (SiC) is one of the most attractive semiconductors for use in high-power and high-temperature regimes, which cannot be satisfied by Si-based devices due to the fundamental physical limitations of Si. SiC is known to have more than 200 polytypes.^{1,2} 4H-SiC epiwafers are commercially available in these polytypes, and their applications to power electronics have been extensively studied. It has been found that stacking faults (SFs) are easily created and developed in 4H-SiC devices during forward-bias stressing^{3,4} or electron-beam (e-beam) irradiation.⁵⁻⁷ Formation and subsequent development of SFs in the active region of devices could be a reason for their degradation.^{8,9} Therefore, the study of SFs has received considerable attention from both the applied and fundamental research communities.

SFs in 4H-SiC have a low formation energy ($\sim 15 \text{ mJ m}^{-2}$),¹⁰ compared with the value of $\sim 55 \text{ mJ m}^{-2}$ for SFs in Si.¹¹ SFs in SiC are commonly generated by dissociating basal plane dislocations (BPDs), with the Burgers vector reaction as follows:

$$\frac{1}{3} [11\bar{2}0] = \frac{1}{3} [10\bar{1}0] + \frac{1}{3} [01\bar{1}0], \quad (1)$$

according to which SFs are created inside partial dislocation loops (PDLs). Generally, the expansion of SFs under device operation is caused by gliding of moving partial dislocations based on the recombination-enhanced dislocation glide (REDG) mechanism.¹²

Using electron-beam-induced current (EBIC) and cathodoluminescence (CL) techniques, we have studied the intrinsic properties of SFs in Schottky diodes.⁵ Since many SiC devices are made on $p-n$ junctions, in this work, we investigated the SF character of $p^+/-n$ junction devices and compared it with that of Schottky diodes. The SF behavior of both devices is discussed.

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EXPERIMENTAL PROCEDURES

Homoepitaxial films with 6 μm thickness were grown on an 8° off-axis 4H-SiC (0001) n^+ substrate by chemical vapour deposition. The dopant was nitrogen with a concentration of $\sim 1.8 \times 10^{16} \text{ cm}^{-3}$. For the $p^+/-n$ specimen, the as-grown film was Al-doped by multiple-energy implantation, forming a $\sim 0.3\text{-}\mu\text{m}$ p^+ layer. Activation annealing was done at a temperature of 1900°C for 1 min using an electron bombardment annealing system.¹³

When performing EBIC measurement for both as-grown and $p^+/-n$ samples, backside ohmic contacts were formed by depositing 200 nm nickel followed by annealing at 1000°C for 5 min, while indium tin oxide (ITO, 100 nm thick) was deposited on the sample surfaces. ITO acts as a Schottky contact for the as-grown specimen while providing an ohmic contact for the $p^+/-n$ sample.

SFs were formed in both samples due to the e-beam irradiation in a scanning electron microscope (SEM, Hitachi S4200). The electrical and optical properties of the SFs were studied simultaneously by using EBIC and CL modes of the SEM.¹⁴ The accelerating voltage and e-beam current were 20 kV and 3 nA, respectively. The recombination activity of a defect is estimated from its EBIC contrast, which is defined by

$$C = \frac{I_{\text{BG}} - I_{\text{D}}}{I_{\text{BG}}} \times 100(\%), \quad (2)$$

where I_{BG} and I_{D} are the EBIC current at the background (BG) and at a defect, respectively.

RESULTS AND DISCUSSION

In order to provide a useful overview, it is proper to begin with a description of intrinsic SFs in 4H-SiC Schottky diodes. In the as-grown homoepitaxial layers, four types of dislocations were found, namely BPD, screw, edge-I, and edge-II, which are electrically active in the order: BPD > screw > edge-I > edge-II.¹⁵ Under e-beam irradiation, a BPD in the Schottky diode easily dissociates to form a SF, as shown in Fig. 1a and b (EBIC images). Initially, a dark line and a dark dot were observed (Fig. 1a). The dark line was parallel to the $\langle 11\bar{2}0 \rangle$ direction, corresponding to the BPD. It intersects with the sample surface at the right end. The single dark dot is a threading dislocation. After 60 min e-beam irradiation (Fig. 1b), the BPD dissociated into a PDL, with a SF forming inside. Note that one partial (marked “I”) stays at nearly the same position as the initial BPD, whereas the other one (marked “M”) moves during the e-beam irradiation. It is interesting to note that the SF shows bright contrast in the EBIC image.

CL measurement was performed in the same region as shown in Fig. 1b. Figure 1c shows the CL spectra taken at BG and SF, respectively. Two main peaks, namely a sharp peak (385 nm) and a broad

Fig. 1. EBIC and CL characterizations of SFs in a Schottky diode: (a) initial EBIC image; (b) EBIC image taken after 60 min e-beam irradiation; (c) CL spectra; (d) monochromatic CL image at wavelength of 417 nm.

peak ($\sim 520 \text{ nm}$), were resolved at the BG. The sharp peak at 385 nm (3.22 eV) is related to the band-edge emission of 4H-SiC. At the SF position, a new peak appears at 417 nm (2.97 eV). A monochromatic CL image at this wavelength is shown in Fig. 1d (the same shape as in Fig. 1b). The solid lines indicate the positions of the immobile (“I”) and mobile (“M”) partials presented in Fig. 1b. The SF region is bright (CL intensity of the SF is ~ 4 times higher than that of the BG) in this image, suggesting that the 417-nm emission originates from the SF. The energy difference between the SF level and the band edge is 0.25 eV, which introduces a quantum-well state below the conduction band of 4H-SiC.^{5,16} It should be noted that the long dashed line indicates the termination of the right side of the SF at the sample surface. The width between those two arrows is $\sim 2.3 \mu\text{m}$, corresponding to a cross-sectional depth of $\sim 0.3 \mu\text{m}$ ($2.3 \times \tan 8^\circ$). The SF in this region is not as bright (CL intensity of the SF in this region is only $\sim 30\%$ higher than that of the BG) in the CL image, which is discussed later.

A model was proposed to explain the bright EBIC contrast of the SF based on the above CL results.⁵ Figure 2 shows a diagram of the sample structure in cross-section. The SF stays in the basal plane that is 8° off-cut to the surface. During the e-beam irradiation, a number of electron-hole (e-h) pairs are generated in an excitation volume. The diameter of this volume is comparable to the electron range of the e-beam, e.g., $\sim 3.5 \mu\text{m}$ at 20 kV.¹⁷ In the as-grown specimen (n -type), minority carriers (holes) move in response to the internal electric field supported by a Schottky contact, producing the EBIC signals for imaging. When the e-beam scans the SF region, a fraction of the electrons generated

Fig. 2. A proposed model explaining the bright SF in the EBIC images.

fall into the SF-related quantum well. Those electrons diffuse away along the SF plane, which results in the reduction of electron density in the excitation volume when compared with that at the BG. Thus, the hole lifetime at the SF increases, giving rise to the bright contrast in the EBIC image.

Figure 3 shows the EBIC images, revealing the dissociation of a BPD in the $p^+/-n$ junction device. Even when we took the initial EBIC image (Fig. 3a), the BPD (whose position is indicated by an arrow) had already dissociated slightly, with a small SF forming inside a PDL. This suggests that the dissociation of BPDs in $p^+/-n$ junctions is faster than that in Schottky diodes. The SF that had expanded after 60 min e-beam irradiation is shown in Fig. 3b. It is seen that not all of the SF is bright. The region marked “E” is shown enlarged in the inset to Fig. 3b. Part “A” is somewhat darker than the BG, while part “B” is brighter. The features observed in the EBIC images of the $p^+/-n$ junction are different from those observed in the Schottky diode. Since the epilayer was grown on an 8° off-cut substrate, the widths of parts “A” and “B” correspond to cross-sectional depths of $\sim 0.3 \mu\text{m}$ and $\sim 0.4 \mu\text{m}$, respectively. Therefore, part “A” may correspond to the Al-doped region (p^+ layer), whereas part “B” is due to the depletion region ($\sim 0.3 \mu\text{m}$).

To highlight the difference of SFs between the Schottky diode and $p^+/-n$ junction, three-dimensional EBIC contrast profiles are shown in Fig. 4. In general, the partials give rise to positive EBIC contrast, while the SFs yield negative contrast (bright in the EBIC images). For the case of the Schottky diode (Fig. 4a), the whole SF region is bright, corresponding to an EBIC contrast of approximately -4% . For the $p^+/-n$ junction device (Fig. 4b), the contrast is markedly less uniform. The rightmost edge of the SF is bright (contrast approximately -4%) and corresponds to where the SF approaches the p^+ layer, whereas the left edge of the SF is less bright (contrast approximately -2%) and corresponds to where the SF penetrates only the n^- region. It is noteworthy that, although the

Fig. 3. EBIC images showing the formation of SFs in the $p^+/-n$ junction device: (a) initial image; (b) after 60 min e-beam irradiation.

Fig. 4. Three-dimensional EBIC contrast profiles of the SFs in both Schottky diode and $p^+/-n$ junction devices.

EBIC contrast of the SF is comparable for both devices, the EBIC contrast of the partials is considerably lower in the $p^+/-n$ junction ($\sim 8\%$) than in the Schottky diode ($\sim 21\%$).

The peculiar behavior of the SF in the $p^+/-n$ junction device can be understood in terms of its CL characteristics. In the CL spectra (Fig. 5a), several new peaks occur at the BG (compared with those in the Schottky diode), especially the intense peak at 482 nm . This peak is commonly referred to as the $Z_{1/2}$ center,^{18,19} which is probably due to Al-implantation processing. These point defects may enhance the gliding of partials, resulting in fast dissociation of BPDs in the $p^+/-n$ junction specimen.

As for the SF, it shows two different characteristics according to the different positions. At SF-X (Fig. 5b), it also has the 417-nm emission peak, similar to that observed for the Schottky diode. However, at SF-Y (right edge part of the SF, indicated by two dashed arrows in Fig. 5b), no such characteristic peak was observed. The width of the SF-Y region is $\sim 4.5 \mu\text{m}$, corresponding to a depth of $\sim 0.6 \mu\text{m}$. These measurements suggest that both the p^+ layer ($\sim 0.3 \mu\text{m}$) and the depletion region ($\sim 0.3 \mu\text{m}$) are dark in the monochromatic CL image, while in the EBIC images (Figs. 3b, 4b) the depletion region shows bright contrast.

Fig. 5. CL measurement done in the $p^+/-n$ junction device: (a) CL spectra; (b) monochromatic CL image at wavelength of 417 nm.

In the $p^+/-n$ junction device, the model proposed in Fig. 2 is also applicable to explain the brightness of the SF in EBIC. The SF in the p^+ layer ("A" in Fig. 3a) is dark. The dark EBIC contrast of the p^+ layer is probably due to band bending at the junction. Because of this band bending, few electrons fall into the quantum well created by the SF in the vicinity of the p^+ layer. As a result, the SF is probably not able to draw the electrons out of the part of the excitation volume within the p^+ layer, which differs from the situation shown in Fig. 2. In the monochromatic CL image (417 nm), the part of the SF penetrating the p^+ layer (SF-Y in Fig. 5b) shows dark contrast. One reason for the lower CL intensity may be that of less recombination occurring that involves the SF energy level and the 4H-SiC valence band edge. A contributing factor could be that of band bending at the junction, which could result in fewer electrons within the SF quantum well. Also, in the Schottky diode (Fig. 1d), no obvious bright contrast was observed in the depletion region. It should be pointed out that, in the depletion region, the internal electric field could also contribute to the reduction in recombination.

CONCLUSIONS

The electrical and optical properties of SFs in the 4H-SiC $p^+/-n$ junction were investigated by using EBIC and CL characterizations. In EBIC, the SFs present bright contrast except those penetrating the p^+ layer, which are different from those observed in the Schottky diode. The proposed quantum-well model is suitable to explain bright SFs in both Schottky diodes and $p^+/-n$ junctions. In CL, only the SF-X region shows the characteristic peak at 417 nm, whereas no such peak was observed in the SF-Y region. Both EBIC and CL contrast effects involving the p^+ layer can be understood in terms of band bending.

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REFERENCES

1. A.R. Verma and P. Krishna, *Polymorphism and Polytypism in Crystals* (New York: Wiley, 1966).
2. N.W. Jepps and T.F. Page, *Progr. Cryst. Growth Charact.* 7, 259 (1983).
3. J.Q. Liu, M. Skowronski, C. Hallin, R. Söderholm, and H. Lendenmann, *Appl. Phys. Lett.* 80, 749 (2002).
4. Z. Zhang, S.I. Maximenko, A. Shrivastava, P. Sadagopan, Y. Gao, and T.S. Sudarshan, *Appl. Phys. Lett.* 88, 062101 (2006).
5. B. Chen, J. Chen, T. Sekiguchi, T. Ohyanagi, H. Matsuhata, A. Kinoshita, H. Okumura, and F. Fabbri, *Appl. Phys. Lett.* 93, 033514 (2008).
6. B. Chen, J. Chen, T. Sekiguchi, T. Ohyanagi, H. Matsuhata, A. Kinoshita, H. Okumura, and F. Fabbri, *Superlattices Microstruct.* 45, 295 (2009).
7. B. Chen, T. Sekiguchi, T. Ohyanagi, H. Matsuhata, A. Kinoshita, and H. Okumura, *J. Appl. Phys.* 106, 074502 (2009).
8. J.P. Bergman, H. Lendenmann, P.Å. Nilsson, U. Lindefeldt, and P. Skytt, *Mater. Sci. Forum* 299, 353 (2001).
9. M. Skowronski and S. Ha, *J. Appl. Phys.* 99, 011101 (2006).
10. P. Pirouz, J.L. Demelet, and M.H. Hong, *Phil. Mag. A* 81, 1207 (2001).
11. H. Iwata, U. Lindefeldt, S. Öberg, and P.R. Briddon, *Phys. Rev. B* 65, 033203 (2001).
12. A. Galeckas, J. Linnros, and P. Pirouz, *Phys. Rev. Lett.* 96, 025502 (2006).
13. M. Shibagaki, M. Satoh, Y. Kurematsu, K. Numajiri, F. Watanabe, S. Haga, K. Miura, T. Suzuki, and S. Miyagawa, *Mater. Sci. Forum* 527–529, 807 (2006).
14. T. Sekiguchi and K. Sumino, *Rev. Sci. Instrum.* 66, 4277 (1995).
15. B. Chen, J. Chen, T. Sekiguchi, A. Kinoshita, H. Matsuhata, H. Yamaguchi, I. Nagai, and H. Okumura, *J. Mater. Sci.: Mater. Electron.* 19, S219 (2008).
16. H. Iwata, U. Lindefeldt, S. Öberg, and P.R. Briddon, *J. Appl. Phys.* 93, 1577 (2003).
17. K. Kanaya and S. Okayama, *J. Phys. D* 5, 43 (1972).
18. T. Dalibor, G. Pensl, H. Matsunami, T. Kimoto, W.J. Choyke, A. Schöner, and N. Nordell, *Phys. Status Solidi A* 162, 199 (1997).
19. L. Storasta, H. Tsuchida, T. Miyazawa, and T. Ohshima, *J. Appl. Phys.* 103, 013705 (2008).