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Relationship between Current Density and Stacking Fault Expansion Origin in Forward Degradation of 4H-SiC PiN Diodes

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Abstract

Relationship between current density and stacking fault expansion origin in forward degradation of 4H-SiC PiN diodes was investigated. In the condition of lower current density, basal-plane dislocations in epitaxial layer formed triangular-shaped stacking faults. In contrast, both triangular- and bar-shaped stacking faults were formed from basal-plane dislocations in substrate converted into threading edge dislocations at the interface between epitaxial layer and substrate in the condition of higher current density. These results indicate that the position with basal-plane dislocation strongly affects the threshold current of the stacking fault expansion.

1. Introduction

In recent years, SiC has been employed in power electronics products because of its high electric-field breakdown strength, high-temperature operation, and high thermal conductivity [1]. However, their reliability has been a crucial issue because SiC wafers have many crystallographic defects. In particular, basal-plane dislocations (BPDs) are known to be the source of forward-current degradation in 4H-SiC bipolar devices [2, 3]. Single Shockley-type stacking fault (1SSF) constituting BPD expands along the basal-plane due to the electron-hole recombination. The 1SSF expansion causes the forward-current degradation of bipolar devices. In order to overcome the forward-current degradation, it is necessary to understand the mechanism of 1SSF expansion in more detail. In this report, we discuss the relationship between a current applying to 4H-SiC PiN diodes and 1SSF expansion.

2. Experimental procedure

An epitaxial layer with a thickness of 10 μm and n = 1.0 x 10^{16} cm^{-3} was grown on a commercially available 345-μm-thick n-type (N-doped, n = 6.4 x 10^{18} cm^{-3}) 4H-SiC (0001) substrate with an offcut angle of 4° toward the [11$\bar{2}$0] direction. For PiN diode fabrication, the anode regions (p = 3.0 x 10^{20} cm^{-3}) were first formed by Al implantation at 500 °C, and then an activation anneal was performed at 1620 °C for 3 min. Electrodes were then formed on both sides. Constant-current stress tests of the PiN diodes were carried out by applying a stress current density step-by-step from 25 to 600 Acm^{-2}. After the stress test, the electrodes of degraded PiN diodes were removed and photoluminescence (PL) imaging was conducted using a 420-nm band-pass filter to clarify positions and shapes of expanded 1SSFs [4]. In order to investigate the expansion origin, grazing incident monochromatic X-ray topography (XRT) with a 0.15-nm wavelength was performed under the diffraction conditions, g = 11$\bar{2}$8, $\bar{1}$1$\bar{2}$8, 1$\bar{2}$18, and $\bar{2}$118. The specimens including the origination point of 1SSF expansion for the transmission electron microscopy (TEM) observations were fabricated by using a focused-ion beam method. The TEM observations were carried out under operating conditions using an acceleration voltage of 1,000 kV with g = 11$\bar{2}$0, 1$\bar{2}$10, and $\bar{2}$110. The Burgers vector of the original BPD (b_{BPD}) was determined by the $g \cdot b$ contrast analysis in TEM observations and the contrast of TED in XRT images with g = 11$\bar{2}$8 and $\bar{1}$1$\bar{2}$8 [5, 6].

3. Result and discussion

Triangular- and bar-shaped 1SSFs were observed in PL images of degraded PiN diodes (Fig. 1(a)). The 1SSF width in the step-flow direction was 143 μm, which indicated that 1SSF expanded in whole epitaxial layer thickness. The histogram of stress current density (J), that the 1SSF expansion was observed, is shown in Fig. 1(b). In the condition of lower J than 25 Acm^{-2}, triangular-shaped 1SSFs were observed. In contrast, bar-shaped 1SSFs were only-observed in the condition of higher J than 350 Acm^{-2}. In order to clarify the relationship between J and the 1SSF shape, the expansion origins were observed using XRT.

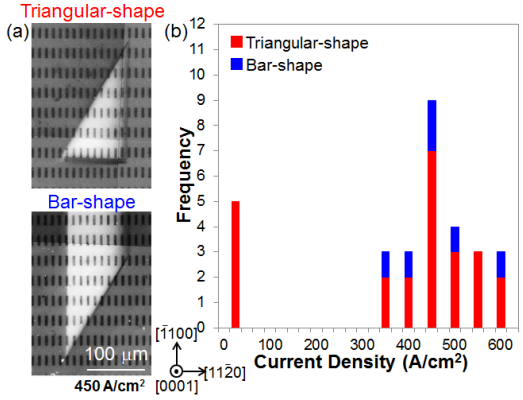

Fig. 1 (a) PL images of expanded 1SSFs and (b) the histogram of J as with color-coded by 1SSF shape.

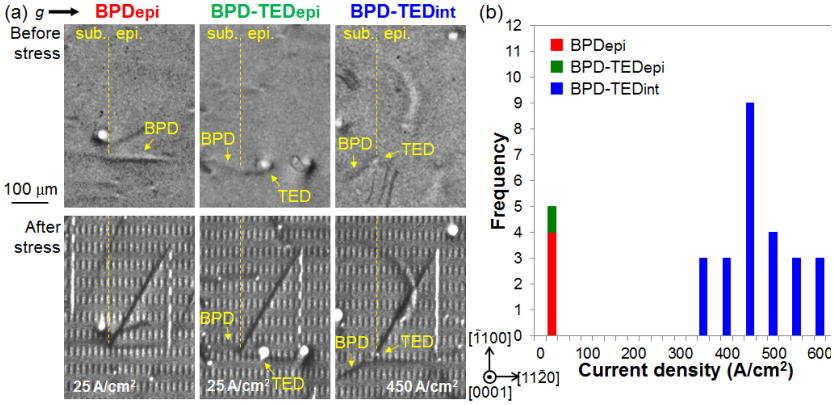

Fig. 2 (a) XRT images of 1SSFs with $g = 11\bar{2}8$ before and after stress current test. (b) The histogram of J as with color-coded by expansion origin.

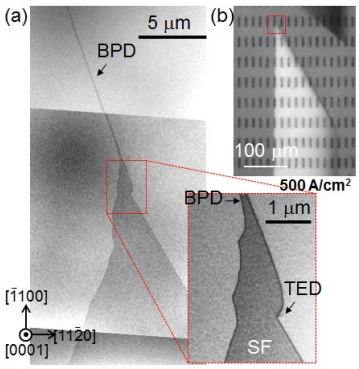

Fig. 3 (a) Plan-view TEM image of the origination point in bar-shape 1SSF shown in (b) PL image.

XRT images at $g = 11\bar{2}8$ for sample before and after stress tests are shown in Figs. 2(a). It was clarified that original BPDs of 1SSF expansion could be classified into three types. The first is BPD propagated from substrate into epitaxial layer (termed as "BPD_{epi}") shown in left of Figs. 2(a). The second is BPD converted into threading edge dislocation (TED) in epitaxial layer (termed as "$BPD\text{-}TED_{epi}$") shown in middle of Figs. 2(a). The third is BPD converted into TED at the interface between the epitaxial layer and substrate (termed as "$BPD\text{-}TED_{int}$") shown in right of Figs. 2(a)). The histogram of J as with color-coded by expansion origin is shown in Fig. 2(b). In the condition of lower J, the expansion origins were BPD_{epi} and $BPD\text{-}TED_{epi}$. Although most BPDs in the substrate are converted into TEDs at the initial stages of the epitaxial film growth process, a part of BPD with $b_{BPD} = \pm 1/3[11\bar{2}0]$ propagates through epitaxial layer from substrate [7]. Thus, 1SSFs expanded to triangular-shapes from BPD_{epi} with $b_{BPD} = \pm 1/3[11\bar{2}0]$ in the condition of lower J [3]. In contrast, the majority of expansion origins in the condition of higher J were $BPD\text{-}TED_{int}$. In this condition, b_{BPD} of original BPDs were any one of $\pm 1/3[11\bar{2}0]$, $\pm 1/3[\bar{2}110]$, or $\pm 1/3[1\bar{2}10]$. The bar-shaped 1SSFs are formed from BPDs with $b_{BPD} = \pm 1/3[\bar{2}110]$ and $\pm 1/3[1\bar{2}10]$ [3]. Then, $BPD\text{-}TED_{int}$ expanded to bar- or triangular-shaped 1SSFs in higher J condition. These results indicate that the threshold J of 1SSF expansion is different on the depth including original BPDs. The 1SSF expansion is caused by the electron-hole recombination [2]. The 1SSF expands from BPD_{epi} under the condition of lower J because the minority carriers are easily injected into BPD in shallow depth. In contrast, $BPD\text{-}TED_{int}$ becomes the 1SSF expansion origin under the condition of higher J that high density minority carriers inject into the substrate. In this experiment, it is suggested that minority carriers are insufficient under the condition of J from 50 to 300 Acm^{-2} for the 1SSF expansion originated $BPD\text{-}TED_{int}$. Also, the 1SSF expansion originating from $BPD\text{-}TED_{int}$ widely distributed from 350 to 600 Acm^{-2} as shown in Fig. 2(b). Thus, the b_{BPD} of each $BPD\text{-}TED_{int}$ was determined to clarify the factor of this wide distribution.

Figure 3(a) shows a plan-view TEM image of the area including the origination point of bar-shaped 1SSF expansion in a red flame shown in PL image of (b). The BPD, consists of two partial dislocations, and TED converted from BPD were observed from enlarged images. From the TEM observations and XRT images, b_{BPD} could be determined as $1/3[\bar{2}110]$. The b_{BPD} for all original BPDs were determined by this technique. As a result, original BPDs with $b_{BPD} = \pm 1/3[11\bar{2}0]$, $\pm 1/3[\bar{2}110]$, and $\pm 1/3[1\bar{2}10]$ were confirmed in the condition of higher J. This result suggests that the reason of large variation in higher J is not b_{BPD} but other factors such as the depth of BPD and strain field.

4. Conclusions

In forward degradation of 4H-SiC PiN diodes, the relationship between J and the expansion origin was investigated using PL, XRT, and TEM. 1SSFs expanded to triangular-shape from BPDs with $b_{BPD} = \pm 1/3[11\bar{2}0]$ in epitaxial layer under the condition of lower J. In the condition of higher J, the expansion origin of triangular- and bar-shaped 1SSFs were BPDs converted into TED at the interface between the epitaxial layer and substrate. From these results, it was clarified that structure of original BPDs strongly affects 1SSF expansion. Also, because 1SSF expansion in higher J was not due to b_{BPD} of the original BPD, it was suggested that other factors affected 1SSF expansion.

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