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Analysis of Forward Bias Degradation Reduction in 4H-SiC PiN Diodes on Bonded Substrates

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Abstract. Analysis of forward bias degradation reduction of 4H-Silicon Carbide (4H-SiC) PiN diodes on bonded substrates was performed. In the analysis, cathodoluminescence (CL), photoluminescence imaging (PL imaging), and transmission electron microscope (TEM) were used. Under high forward bias stress, the Shockley-type stacking fault (SSF) does not expand into the transferred layer of the bonded substrate, while in the monocrystalline substrate, the SSF expands below the epilayer/substrate interface. The basal plane dislocation (BPD) within the transferred layer does not expand to the SSF. The transferred layer has the effect of suppressing the expansion of SSFs. This effect can be caused by hydrogen implantation for wafer splitting to produce bonded SiC substrates.

Introduction

4H-SiC is a promising wide-gap material for high-power electrical devices due to its high breakdown field and high thermal conductivity. Currently, 4H-SiC bonded substrates are being put into practical use for power devices. SICOXS's bonded substrate (SiCkrest) has a structure in which a thin monocrystalline layer of 1 μm or less (transferred layer) is bonded to a low-resistance n-type polycrystalline substrate by the surface activated bonding method. The bonded substrate brings some benefits, such as reduction of on-resistance in PiN diodes and backside ohmic contact formation without annealing.

Forward bias degradation is widely observed during 4H-SiC bipolar operation. In this phenomenon, the on-voltage increases in response to forward current stress. This is due to the expansion of SSFs starting from BPDs caused by the recombination of electron-hole pairs [1]. The driving force of SSF expansion was proposed to be electron energy gain due to carrier trapping in SSFs [2]. We reported that the bonded substrate reduces the forward bias degradation in PiN diodes [3]. On the monocrystalline substrate, the forward voltage shift abruptly increases at the forward current stress less than 1000 A/cm^2, while on the bonded substrate, the forward voltage shift hardly increases.

As a mechanism of forward bias degradation reduction in the bonded substrates, the BPD reduction associated with TED glide was proposed [3]. The forward bias degradation is suppressed as TED glide increases in the monocrystalline substrates [4, 5]. Even for the bonded substrates, the BPD-TED conversion causes a TED glide, which moves the conversion point to downward within the transferred layer which suppresses the expansion of SSFs.

The transferred layer is less than 1 μm which is nearly three orders of magnitude thinner than the 350 μm thick monocrystalline substrate. Hydrogen implantation is used for wafer splitting to fabricate the bonded substrate with the thin transferred layer. It is considered that the hydrogen implantation affects the crystal property of the transferred layer, so the expansion of SSF in the transferred layer may behave differently from that in the monocrystalline substrate. In this study, we investigated the influence of the thin transferred layer on the expansion of SSFs.

Experimental

In PiN diodes used in this study, a lightly N-doped epitaxial layer was homoepitaxially formed. The dopant concentration and thickness of epitaxial layer are 1×10^{16} /cm^3 and 10 µm, respectively. A p^+ anode region with a dopant concentration of 3×10^{20} /cm^3 was fabricated using aluminum implantation at 500 °C followed by activation annealing at 1620 °C. Finally, anodes and cathodes were formed on both sides of the substrate to obtain PiN diodes. The active area is 0.038 cm^2.

The analysis methods are CL, PL imaging, and TEM. For all analysis samples, the electrodes were removed after the forward current stress tests. For cross-sectional CL samples, the chip cross-section was mechanically polished, and the damaged layer was removed by argon ion milling. The cross-sectional surfaces of the samples were measured at intervals of about 0.16 µm from the epitaxial layer to the substrate at 30 K. The acceleration voltage of the electron beam is 7 kV, and the penetration depth in SiC is about 0.58 µm. In the PL imaging measurement, SSFs in the epitaxial layers can be detected with using a 420 nm bandpass filter. A cross-sectional TEM tilted vertically was used to distinguish between SSFs and BPDs.

Results and Discussion

1. Cross-sectional CL measurements after forward current stress

Fig. 1 shows the CL spectra in the wavelength range near the band-edge emission for PiN diodes on monocrystalline and bonded substrates. The luminescence intensity is offset for clarity. Near-band-edge emission was observed in the epitaxial layer and the monocrystalline substrate, but not in the transferred layer and the polycrystalline substrate. The monocrystalline substrate and the transferred layer of the bonded substrate have different crystal property that affect near-band-edge emission. It is likely that there are non-radiative recombination centers in the transferred layer.

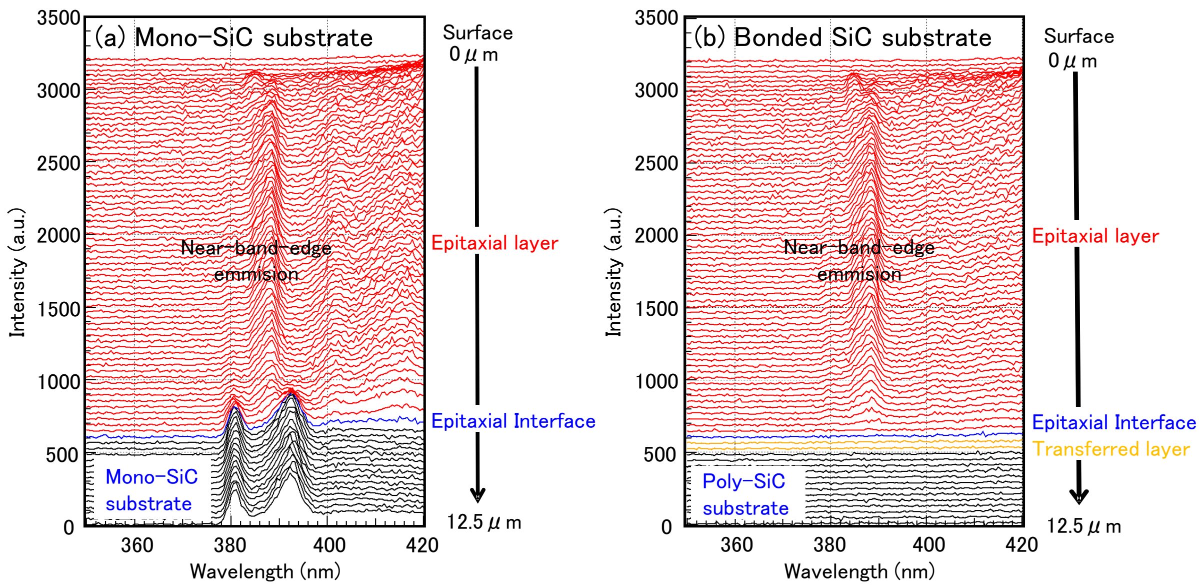

Fig. 1. CL spectra in the wavelength range near the band-edge emission for (a) a PiN diode on a monocrystalline substrate and (b) a PiN diode on a bonded substrate.

2. Comparison of TEM images of bar-shaped SSFs for monocrystalline and bonded substrates

Fig. 2 illustrates PL images of bar-shaped SSFs in the epitaxial layers for PiN diodes on monocrystalline and bonded substrates after high forward current stress tests. Although the number of bar-shaped SSFs of bonded substrates were much smaller than that of the monocrystalline substrate, we were able to find expanded bar-shaped SSFs from within the epitaxial layer. Since the monocrystalline region is tilted by 4°, the left end of the stacking faults corresponds to the epilayer/substrate interface. In order to visualize the SSFs near the epitaxial interface, TEM observation was conducted at the yellow frame of both samples.

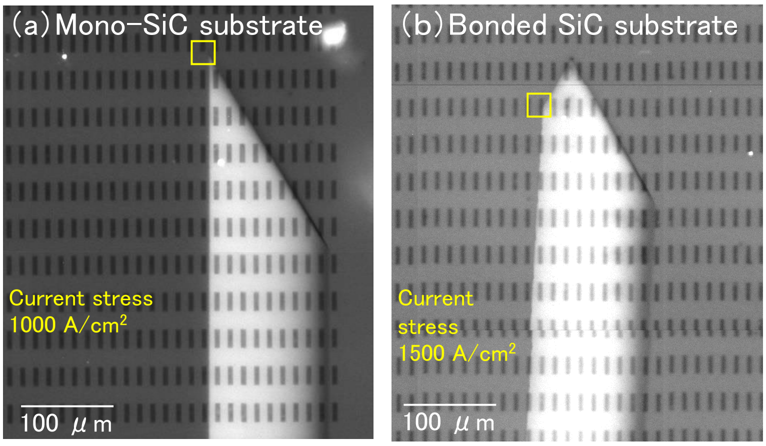

Fig. 2. PL images of (a) a PiN diode on a monocrystalline substrate after applying a current density of 1000 A/cm^2 and (b) a PiN diode on a bonded substrate after applying a current density of 1500 A/cm^2.

Fig. 3 shows cross-sectional TEM images of the bonded substrate observed under not tilted condition (Fig. 3(a)) and vertically tilted condition (Fig. 3(b)). Under not tilted condition, a partial dislocation is observed near the interface of the epilayer and the transferred layer. When the TEM sample is tilted, the moire fringe of SSF is clearly visible. Under the vertically tilted condition, the width of the interface increases depending on the amount of tilt, so the regions of the epitaxial layer and transferred layer are indicated by white arrows.

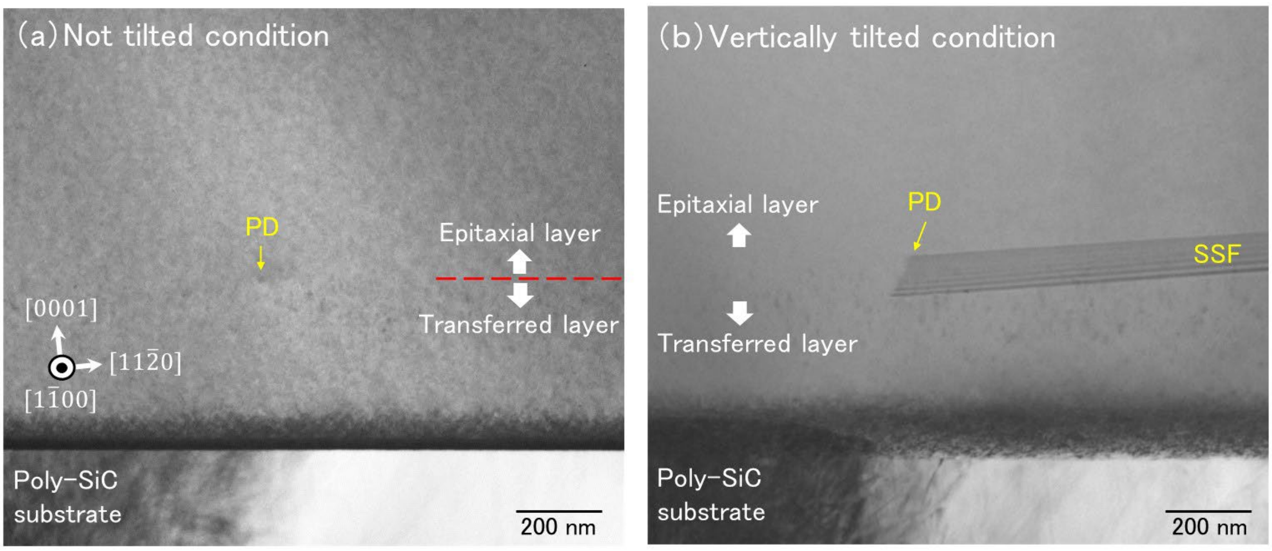

Fig. 3. Cross-sectional TEM images of a PiN diode on a bonded substrate after applying a current density of 1500 A/cm^2 in the [1$\bar{1}$00] direction (a) under not tilted condition (Zone axis alignment condition) and (b) vertically tilted condition.

A comparison of cross-sectional TEM images for a monocrystalline and a bonded substrate under vertically tilted condition is shown in Fig. 4. In the monocrystalline substrate, a BPD converted to a treading edge dislocation (TED) near the epilayer/substrate interface expands to a SSF. In the bonded substrate, the SSF expands downward from the epitaxial layer, but stops in the vicinity of the interface of epilayer and transferred layer, indicating that SSFs do not expand into the transferred layer.

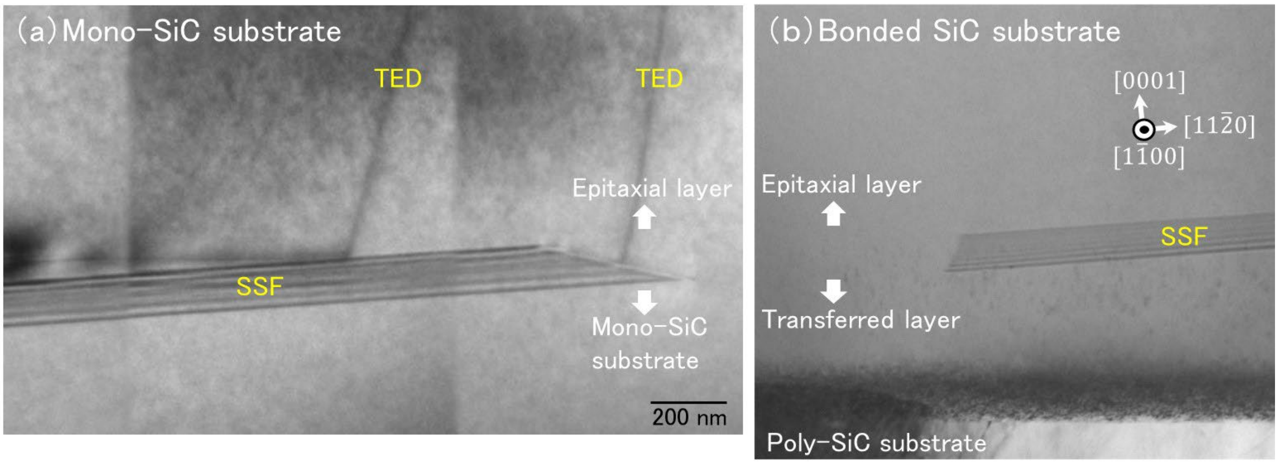

Fig. 4. Cross-sectional TEM images of (a) a PiN diode on a monocrystalline substrate and (b) a PiN diode on a bonded substrate in the $[1\bar{1}00]$ direction under vertically tilted condition.

A low-magnification cross-sectional TEM image of a SSF expanded into a monocrystalline substrate under vertically tilted condition is illustrated in Fig. 5. The SSF expands more than 1 μm below the epilayer/substrate interface. This result indicates that the SSF tends to expand into the monocrystalline substrate under the high forward current stress.

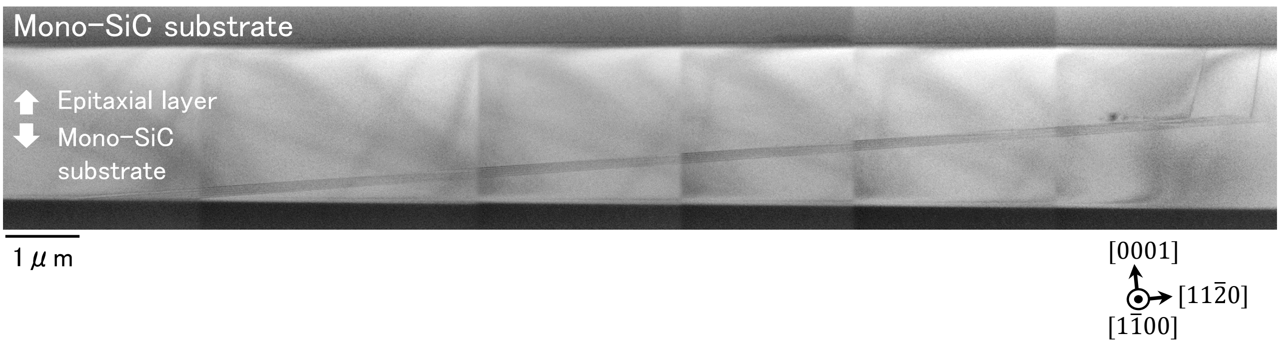

Fig. 5. Low-magnification cross-sectional TEM image for a PiN diode on a monocrystalline substrate in the $[1\bar{1}00]$ direction under vertically tilted condition.

3. STEM Observation of a BPD Inside the Transferred Layer of Bonded Substrate

A BPD in the transferred layer of bonded substrate was found in a triangular SSF in the epitaxial layer after high forward current stress. In the PL image in Fig. 6 (a), a triangular SSF is observed, and the leftmost vertex of the SSF indicates the vicinity of the interface of epilayer and transferred layer. The plan-view STEM image of this region is shown in Fig. 6 (b). Fig. 6 (c) illustrates the schematic drawing of the defects showing a SSF surrounded by partial dislocations (PDs), a BPD and two TEDs. The BPD within the transferred layer near the interface of epilayer and transferred layer does not expand to a SSF during the forward bias stress.

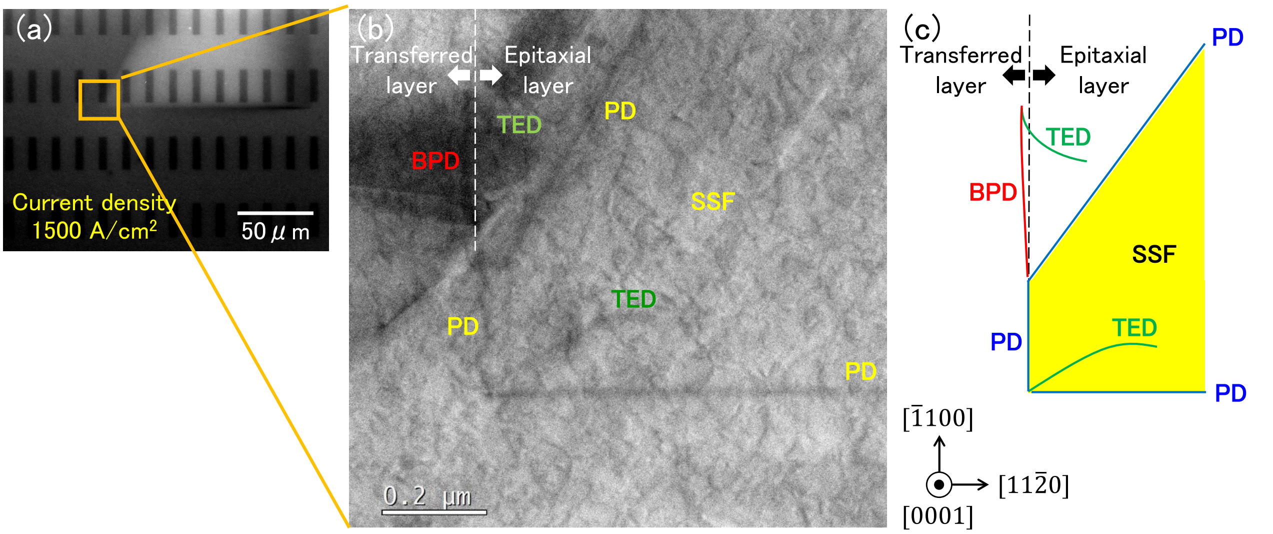

Fig. 6. (a) PL image and (b) plan-view STEM image of a PiN diode on a bonded substrate after applying a current density of 1500 A/cm^2. (c) Schematic drawing of the plan-view STEM image.

Fig. 7 (a) shows a cross-sectional STEM image for a bonded substrate in the $[\bar{1}\bar{1}20]$ direction under vertically tilted condition. The schematic drawings of cross-sectional and plan-view STEM images are also shown in Figs. 7 (b) and (c), respectively. Since the stacking fault has a width under vertically tilted condition, BPDs and SSFs can be distinguished. It is found from the STEM image that under the forward current stress, the BPD does not expand to a SSF within the transferred layer, but expands to a SSF in the epitaxial layer.

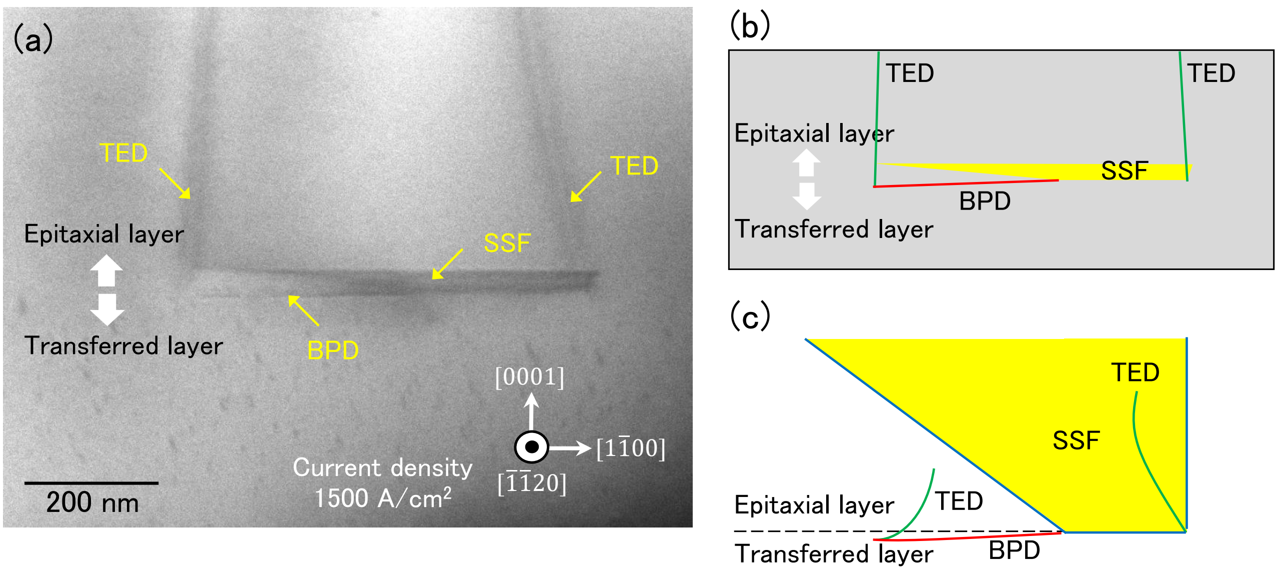

Fig. 7. (a) Cross-sectional STEM image of a PiN diode on a bonded substrate after applying a current density of 1500 A/cm^2 in the $[\bar{1}\bar{1}20]$ direction under vertically tilted condition. Schematic drawings of (b) the cross-sectional STEM image and (c) the plan-view STEM image.

The TEM observation results reveal that the transferred layer of the bonded substrate has the effect of suppressing the expansion of SSFs. It is likely that the suppression effect is caused by hydrogen implantation for wafer splitting to produce bonded substrates. Two mechanisms of SSF expansion suppression by hydrogen implantation are predicted. One is the creation of recombination centers in the transferred layer estimated from the cross-sectional CL measurement results. The recombination centers created by hydrogen implantation promote the recombination of electrons and holes, so that holes are rapidly annihilated in the transferred layer. The other is point defects in the transferred layer.

It has been reported that in monocrystalline substrates, the point defects created by hydrogen implantation suppress the dislocation glide motion [6, 7]. It is predicted that these two phenomena occur within the transfer layer. However, the mechanism of suppressing SSF expansion in the bonded substrates is not fully understood, and further evaluation is required to clarify it.

Summary

We analyzed the forward bias degradation reduction of 4H-SiC PiN diodes on bonded substrates. CL, PL imaging, and TEM were used for analysis. Under high forward bias stress, the SSF does not expand into the transferred layer of the bonded substrate, while the SSF expands under the epilayer/substrate interface into the monocrystalline substrate. The BPD within the transferred layer does not expand to the SSF. The transferred layer has the effect of suppressing the expansion of SSF. The suppression effect can be caused by hydrogen implantation for wafer splitting to produce bonded SiC substrates.

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