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Observations of Overlapped Single Shockley Stacking Faults in 4H-SiC PiN Diode

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In 4H-SiC PiN diodes, Shockley-type stacking faults expand from basal plane dislocations under conducting forward current. We report for the first time overlapped single Shockley-type stacking faults in a 4H-SiC PiN diode after forward conduction. In photoluminescence measurements, we observed not only an emission peak at 425 nm, which corresponds to the single Shockley-type stacking fault, but also one at 432 nm. In cross-sectional cathode luminescence images, emission lines at 425 nm and 432 nm merge and become straight. Transmission electron microscope images showed that the structure at the position with the 432 nm emission overlapped the single Shockley-type stacking faults.

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1. Introduction

In 4H-SiC, stacking faults (SFs) form a level within the band gap and emit at a specific wavelength that corresponds to the level in each structure [1]. Therefore, it is possible to determine the structure of an SF by investigating the wavelength of the SF emission. The forward voltage drop of a 4H-SiC PiN diode increases under conducting forward current by expanding SFs in the drift layer. An expanded SF emitting at 425 nm has been reported to be a Shockley-type stacking fault (SSF) [2]. In the present work, we obtained photoluminescence (PL) images, PL spectra, and cathode luminescence (CL) images of a 4H-SiC PiN diode after a current stress test. As a result, we observed not only an emission at 425 nm but also an emission at 432 nm that had not been previously reported. We investigated SFs emitting at 432 nm in a 4H-SiC PiN diode with a transmission electron microscope (TEM).

2. Experimental method

Figure 1 shows the device structure of a fabricated 4H-SiC PiN diode. The n^- drift layer and p^+ anode layer were grown on 8° off-cut n^+ 4H-SiC substrate by epitaxial growth in a vertical hot-wall reactor [3]. The substrates used in this work were n-type (0001) 4H-SiC wafers tilted at 8° toward ⟨11–20⟩. The thickness and donor concentration of the n^- drift layer were 120 μm and 7×10^{13} cm^{-3}, respectively. The thickness of the p^+ anode layer was 3 μm. The mesa structure was produced by reactive ion etching. The height of the mesa was approximately 4 μm. No junction termination extension (JTE) structure was formed, and the surface of the mesa was not covered with an oxide layer by thermal oxidation, because we evaluated only forward characteristics. The diode active area was 1.0 mm × 1.0 mm. The current stress test was conducted at 100 A/cm^2 for 1 h. A He–Cd laser was used as an excitation light for PL measurement. PL images and spectra were observed at 77 K. CL images were taken at 35 K. The accelerating voltage was 15 kV.

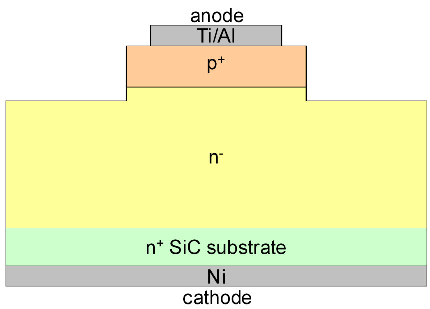

Fig. 1. Device structure of a fabricated 4H-SiC PiN diode.

3. Results and discussion

3.1. Photoluminescence images and spectra

Figure 2 shows the PL image of the 4H-SiC PiN diode after the current stress test emitting at 425 nm. Bright areas correspond to SSFs because the emission at 425 nm is reported to be an SSF [2]. The observed SSF is rectangular in shape. The SSF extends over the full length of the device with a width of 0.27 mm. The basal plane,

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in which the SSF is expanded, is tilted 8° from the surface, and the width of the basal plane in the drift layer is calculated to be 0.85 mm. The entirety of the SSF cannot be observed, because of a short penetration depth of the excitation light. We observed PL spectra at each indicated point in Fig. 2.

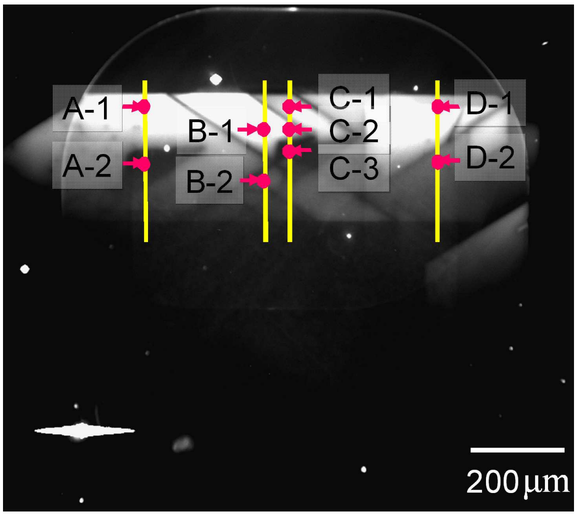

Fig. 2. PL image of the 4H-SiC PiN diode emitting at 425 nm after the current stress test. Bright areas correspond to SSFs. PL spectra were measured at the indicated points in this figure.

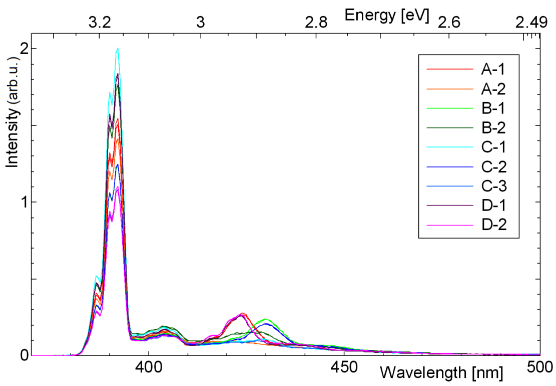

Fig. 3. PL spectra of the 4H-SiC PiN diode after the current stress test at each indicated point in Fig. 2.

Figure 3 shows the PL spectra at each point. The peaks around 390 nm and 405 nm are attributed to donor-bound excitations and phonon replicas, respectively. In addition, a 425 nm peak indicated the presence of an SSF. In contrast, a previously unknown 432 nm peak with a structure was observed.

3.2. Cathode luminescence images

The CL images were taken at the cross-section of the 4H-SiC PiN diode along the C–1 to C–3 lines shown in Fig. 2.

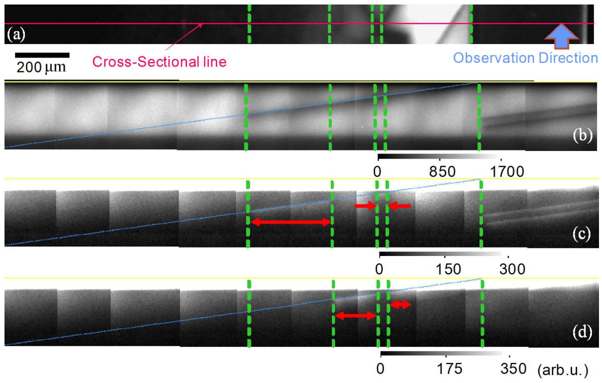

Fig. 4. (a) The area near the points C–1 to C–3 in Fig. 3 is magnified and rotated 90°. The cross-sectional CL images of the 4H-SiC PiN diode after the current stress test emitting at (b) 388 nm, (c) 425 nm, and (d) 432 nm.

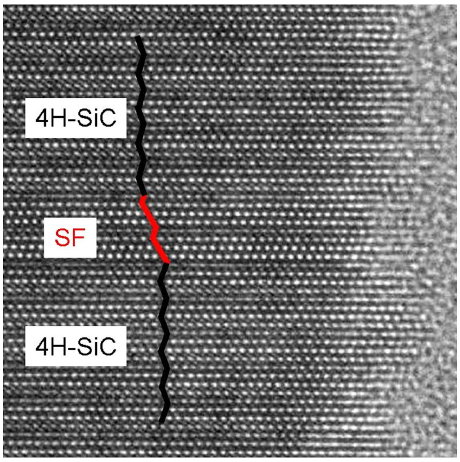

Fig. 5. TEM image of an SF emitting at 432 nm in the 4H-SiC PiN diode.

Figure 4 shows the cross-sectional CL images of the 4H-SiC PiN diode emitting at 388, 425, and 432 nm after the current stress test. In Fig. 4b, the dark areas indicate the presence of some defects. The emission at 388 nm indicates a donor and acceptor pair excitation. Other emissions, such as those from defects, become dominant in the dark areas. The dark line is tilted 8° from the surface, and breaks at a depth of 120 μm. The expansion motion of SSFs from basal plane dislocations (BPDs) in the drift layer is caused by electron–hole recombination. In high-level injection for the 4H-SiC PiN diode, electrons and holes are injected into the drift layer and recombine with each other. Thus, the electron–hole recombination occurs in the only drift layer, and the dark line exists only in the drift layer. Bright areas in Fig. 4c and d correspond to SSFs and some type of SFs, respectively. Although the bright lines in each image are discontinuous, when Fig. 4c is superimposed on Fig. 4d, the bright lines form a continuous straight line. Therefore, SSFs and some type of SFs exist alternately in the series of defects.

3.3. Transmission electron microscope images

Figure 5 shows a TEM image of an SF emitting at 432 nm in a 4H-SiC PiN diode. There are two continuous layers of SSF in SF emitting at 432 nm. The expanding SF reaches the threading screw dislocation (TSD). Then, the SF shifts by 1c and starts expanding again [4]. The SF emitting at 432 nm overlaps with the SSF, which was caused by the TSD present in the drift layer.

4. Conclusions

For 4H-SiC PiN diodes, SSFs expand from BPDs under conducting forward current. We report for the first time overlapped SSFs in the 4H-SiC PiN diode after a forward conduction. In the PL measurement, we observed not only an emission peak at 425 nm, which corresponds to the SSF, but also one at 432 nm. In the cross-sectional CL images, emission lines at 425 nm and 432 nm form a continuous straight line. TEM images showed that the structure at the position with 432 nm emission is overlapped SSFs.

Acknowledgments

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