High-Quality SiC Epitaxial Wafer “EpiEra” Realizing High-Reliability Large-Current Power Devices

Hironori ITOH*, Taro ENOKIZONO, Takaya MIYASE, Tsutomu HORI, Keiji WADA, and Masaki FURUMAI

Silicon carbide (SiC) power devices are promising next-generation devices and their market is growing globally year by year. The quality of SiC epitaxial wafers is particularly important to secure the reliability of large-current power devices used for automotive applications. Basal plane dislocation (BPD) in the SiC epitaxial wafers causes stacking fault expansion, which leads to the fatal degradation of SiC bipolar devices. To suppress the stacking fault expansion, the introduction of highly nitrogen-doped layer called a “recombination-enhancing layer” has been proposed. In this study, we have established a method to evaluate BPD in the recombination-enhancing layer by investigating the receiving filter using photoluminescence imaging, and successfully obtained a 150 mm SiC epitaxial wafer with extremely low BPD density. We also confirmed that BPD and surface defects in the drift layer were simultaneously suppressed, demonstrating the new epitaxial wafer has stable characteristics for large chip devices.

Keywords: SiC, power device, epitaxial growth, BPD, recombination-enhancing buffer layer

1. Introduction

The silicon carbide (SiC) power devices are a type of highly efficient next-generation power devices that replace Si. The market of these devices has been rapidly expanding. In large-current applications (e.g., in-vehicle applications), increasing the chip size of devices has become a growing demand. Improving the quality of the SiC epitaxial layer, a major determinant of the device yield, is particularly important. In 2017, we started mass production of the SiC epitaxial substrates (product name: EpiEra) that attained superb within-wafer thickness, doping uniformity, and low defects density.(1)

Generally, a SiC substrate has basal plane dislocations (BPDs)*1, threading edge dislocations (TEDs)*2, threading screw dislocations (TSDs), and mixed dislocations with the density of several hundred to several thousand cm^{-2}. BPDs are known to trigger Shockley stacking fault expansion in the minority carrier recombination process of the forward direction energization operation in bipolar devices and cause fatal degradation of the device reliability.(2) Consequently, a process technology(3),(4) is necessary to convert BPDs, which are contained in the substrate, into TEDs, which are considered harmless to devices, in the epitaxial growth.

Previously, BPD–TED conversion in the epitaxial growth layer had been considered appropriate. However, a new report revealed that BPDs in the substrate could cause the abovementioned stacking fault expansion, particularly in a large-current condition.(5) To address this problem, a technology to prevent stacking faults from BPDs in the substrate has been proposed by introducing the recombination-enhancing buffer layer, an epitaxial layer doped with high-concentration impurity nitrogen.(6),(7)

As shown in Fig. 1, in the so-called normal buffer layer (thickness: 1 μm or less, impurity concentration: 1 × 10^{18} cm^{-3} or less in general), electron holes in the drift layer reach BPDs in the substrate and cause the stacking fault expansion during the high-current device operation. Meanwhile, in the recombination-enhancing buffer layer doped with higher-concentration impurity nitrogen with increased film thickness (e.g., thickness: 3 μm or more, impurity concentration: 2 × 10^{18} cm^{-3} or more), the stacking fault expansion from BPDs in the substrate can be prevented by making the electron holes disappear in the recombination-enhancing buffer layer.

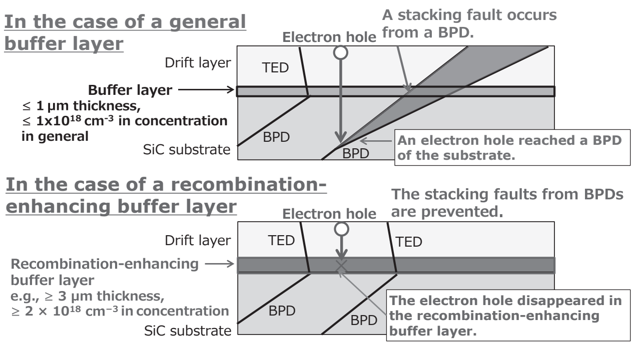


Fig. 1. Role of the recombination-enhancing buffer layer in a SiC epitaxial substrate (in comparison with a general buffer layer)

When introducing such a recombination-enhancing buffer layer, BPDs must be ensured to be sufficiently low by BPD–TED conversion in the substrate. A previous research reported BPD evaluation in the recombination-enhancing buffer layer based on the synchrotron X-ray diffraction topography.(6) Regarding the evaluation method in the SiC epitaxial substrate manufacturing process, a different BPD evaluation technique that is easier and nondestructive is required.

This paper reports the BPD evaluation technique in the recombination-enhancing buffer layer using the photoluminescence (PL) imaging measurement method and a high-quality 150 mm SiC epitaxial substrate achieved in the development project to reduce BPDs in the recombination-enhancing buffer layer.

2. SiC Epitaxial Growth and Evaluation

A SiC epitaxial layer was formed using a hot-wall chemical vapor deposition reactor capable of forming the layer on multiple 150 mm substrates at the same time. In this experiment, 150 mm 4°-off Si surface 4H-SiC substrates were used. We used monosilane and propane as the source gases, hydrogen as the carrier gas, and nitrogen as the dopant.

The film thickness of the SiC epitaxial growth layer was calculated based on the optical interference analysis using a Fourier transform infrared spectrometer. The impurity concentration was calculated based on the depletion layer analysis using the capacitance–voltage measurement. The surface defects in the epitaxial growth layer were observed and counted using a confocal optical microscope with a stage system. BPDs that propagated from the substrate were observed and evaluated by PL imaging at room temperature. A Hg–Xe UV lamp was used as the light source for the PL imaging measurement. A 313 nm band-pass filter was used as the excitation filter. For the light-receiving filter, a > 750 nm long-pass filter or an improved filter was used. Here, improved filter refers to a filter optimized for detecting BPDs in the high-concentration nitrogen-doped layer.

3. BPD–TED Conversion Position

The present study had found that BPD–TED conversion occurs mainly at two positions in the SiC epitaxial growth (Fig. 2). That is, BPDs are converted to TEDs at the interface (i) between the recombination-enhancing buffer layer and the drift layer and (ii) between the substrate and the recombination-enhancing buffer layer. In both cases, the number of BPDs in the drift layer is sufficiently low, but the number of BPDs in the recombination-enhancing buffer layer may be high or low. Therefore, BPD evaluation in the drift layer alone cannot guarantee that the number of BPDs is low in the recombination-enhancing buffer layer.

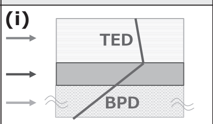
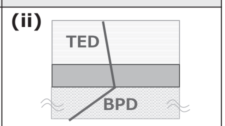
	Schematic diagrams of the cross section of epitaxial substrates			
BPD conversion position	Interface between the recombination-enhancing buffer layer and the drift layer		Interface between the substrate and the recombination-enhancing buffer layer	
Drift layer → Recombination-enhancing buffer layer → SiC substrate →	(i) 		(ii) 	
Epitaxial layer	Recombination-enhancing buffer layer	Drift layer	Recombination-enhancing buffer layer	Drift layer
Presence of BPD	Yes	No	No	No

Fig. 2. Expected BPD–TED conversion position in the SiC epitaxial growth

4. Detection of BPDs in the Recombination-Enhancing Buffer Layer

Conventionally, the evaluation target of BPDs in the SiC epitaxial layer by means of the PL imaging measurement was limited only to the drift layer.(8) This is because the PL from the background (other than BPDs) is too strong in the general buffer layer and the recombination-enhancing buffer layer, which are characterized by high nitrogen concentration compared with the drift layer in general, making detection of BPDs difficult. However, to guarantee a low density of BPDs in the recombination-enhancing buffer layer as shown in Fig. 2, it is necessary to detect and evaluate BPDs that are present in the recombination-enhancing buffer layer. Thus, we studied light-receiving filters used in the PL imaging measurement.

Examples of BPD detection in the recombination-enhancing buffer layer are shown in Figs. 3 and 4. The recombination-enhancing buffer layer is 8 μm in thickness and 2×10^{18} cm^{-3} in concentration, and the drift layer is 10

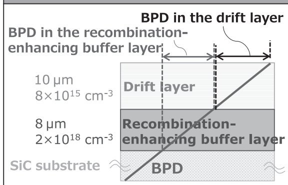
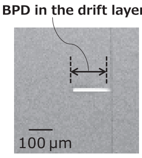
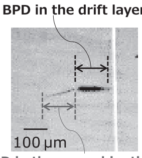
Schematic diagram of the cross section of the epitaxial substrate		Comparison of the PL image	
		Using a > 750 nm filter	Using an improved filter
			
BPD detection capability	Drift layer	Yes	Yes
	Recombination-enhancing buffer layer	No	Yes

Fig. 3. Example of BPD detection in the recombination-enhancing buffer layer (a case in which BPD conversion did not occur in the epitaxial layer)

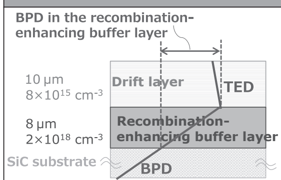
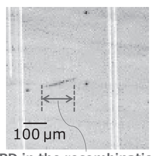
Schematic diagram of the cross section of the epitaxial substrate		Comparison of the PL image	
		Using a > 750 nm filter	Using an improved filter
			
BPD detection capability	Drift layer	Yes	Yes
	Recombination-enhancing buffer layer	No	Yes

Fig. 4. Example of BPD detection in the recombination-enhancing buffer layer (a case in which BPD conversion occurred at the interface between the recombination-enhancing buffer layer and the drift layer)

μm in thickness and 8 × 10^{15} cm^{-3} in concentration. An example in which BPD conversion did not occur in the epitaxial layer is shown in Fig. 3. To compare the PL images captured using different light-receiving filters, the figure indicates images captured using the > 750 nm long-pass filter and the improved filter. When the > 750 nm long-pass filter was used, only BPDs in the drift layer were detected as a white straight line. BPDs in the recombination-enhancing buffer layer were not detected at all. When the improved filter was used, both BPDs in the drift layer and those in the recombination-enhancing buffer layer were clearly detected as a black straight line.

The use of the improved filter was confirmed to enable detection of BPDs in the high-concentration layer (e.g., recombination-enhancing buffer layer), which was considered to be difficult to attain via the conventional PL imaging method. Another example of BPD–TED conversion at the interface between the recombination-enhancing buffer layer and the drift layer is shown in Fig. 4. It indicates that BPDs in the recombination-enhancing buffer layer are detected on the PL image only when the improved filter is used, as in the case in Fig. 3.

5. Reduction of BPDs in the Recombination-Enhancing Buffer Layer

We worked to reduce the BPDs in the recombination-enhancing buffer layer on the basis of the BPD evaluation technique. To study the BPD reduction condition, the BPD density was compared using samples in which only the recombination-enhancing buffer layer (thickness: 8 μm, concentration: 2 × 10^{18} cm^{-3}) was allowed to grow.

The BPD count maps (2.6 mm square cells) before and after the BPD density reduction are shown in Fig. 5. The improved filter was used for BPD detection. Before the improvement of the epitaxial growth condition of the recombination-enhancing buffer layer, many BPDs were detected. The BPD density was 70 cm^{-2}. As we optimized the epitaxial growth condition of the recombination-enhancing buffer layer, the BPD density was significantly reduced to 0.03 cm^{-2}, as shown in the map on the right side of Fig. 5.

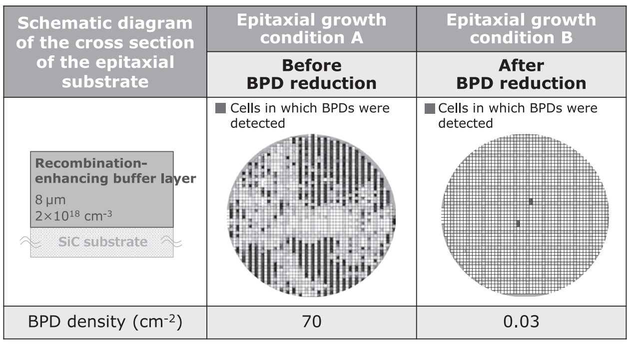


Fig. 5. Results of study of BPD reduction in the recombination-enhancing buffer layer (using an improved filter for BPD detection)

6. Evaluation Results of the Drift Layer

BPDs of samples in which the drift layer was allowed to grow on the optimized recombination-enhancing buffer layer and the evaluation results of the surface defects are shown in Fig. 6. A long-pass filter of > 750 nm was used to detect only BPDs in the drift layer. The BPD density of the drift layer was 0.01 cm^{-2}, and the surface defect (down-fall + triangular defects) density was 0.04 cm^{-2}. It was confirmed that both the BPD quality of the recombination-enhancing buffer layer and the defect quality of the drift layer can be ensured at the same time.

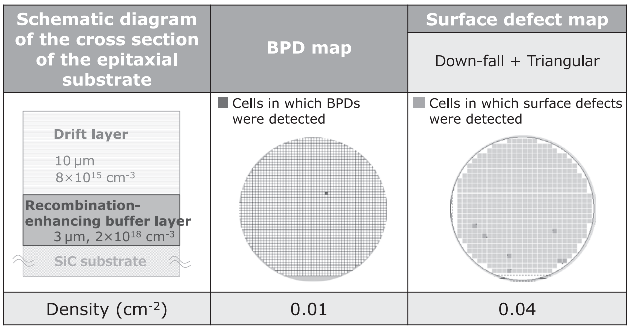


Fig. 6. Evaluation results of BPDs and surface defects in the drift layer of the recombination-enhancing buffer layer (using a > 750 nm long-pass filter for BPD detection)

7. Conclusion

We studied the BPD evaluation technique in the recombination-enhancing buffer layer using the PL imaging method and developed a high-quality 150 mm SiC epitaxial substrate with a recombination-enhancing buffer layer. Through the use of an optimal light-receiving filter, BPDs in the recombination-enhancing buffer layer, which was difficult to attain using the conventional PL imaging method, can be clearly detected.

We succeeded in reducing the BPDs in the recombination-enhancing buffer layer to a level that can be practically regarded as BPD-free (0.03 cm^{-2}) by optimizing the epitaxial growth condition. Both BPD quality and surface defect quality of the drift layer are ensured. Thus, the products are considered to be optimal for in-vehicle devices, in particular, which are required to be highly reliable in large-current applications.

Our EpiEra products are already characterized by high uniformity for its epitaxial thickness and doping concentration in the 150 mm wafer.[9] They contribute to ensuring stable properties of large-area SiC devices.

• EpiEra is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.

Technical Terms

∗1 Basal plane dislocation (BPD): Dislocation that is observed on the basal plane and has Burgers vectors of <11-20>/3.

∗2 Threading edge dislocation (TED): Edge dislocation that propagates in near-parallel with the crystal c-axis and has Burgers vectors of <11-20>/3.

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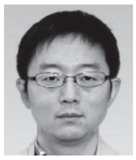

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