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Accuracy of EVC Method for the PiN Diode Pattern on SiC Epi-Wafer

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Abstract. In the previous report, we proposed the EVC (Expansion-Visualization-Contraction) method (Fig. 1) that effectively screens for malignant BPDs (basal plane dislocations) in the epi layer and near substrate interface, which expand to SSFs (Shockley-type stacking faults), leading to forward voltage degradation. The method intentionally utilizes the REDG (recombination enhanced dislocation glide) mechanism by UV (ultraviolet) irradiation in wafer sorting to replace the so-called burn-in (accelerated current stress) process, which is time-consuming during mass production.

In this report, to verify the effectiveness of this method, we compared the SSFs expanded by forward biasing the PiN diode (Fig.3) on a wafer with the SSFs expanded by UV irradiating at the same PiN diode area where the metal electrode was removed by etching. The accuracy of the EVC method requires that SSFs expanded by forward biasing should be detected in the same positions as those of SSFs expanded by UV irradiation.

Not all BPDs expand at the same time, but the number of expanded SSFs increases over time under constant forward current conditions. In this experiment, the current density was 400 A/cm^2 for 8 minutes, and the excessive UV irradiation conditions was 143 W/cm^2 for 20 minutes to avoid missing. Missing means the inability to check the SSFs expanded by forward biasing against the SSFs expanded by UV irradiation (Fig.2). For each diode electrode window, the presence or absence of SSFs were determined, and as shown in Table 2, 2 out of 49 window areas were missing, with the EVC method accuracy rate of 96 %.

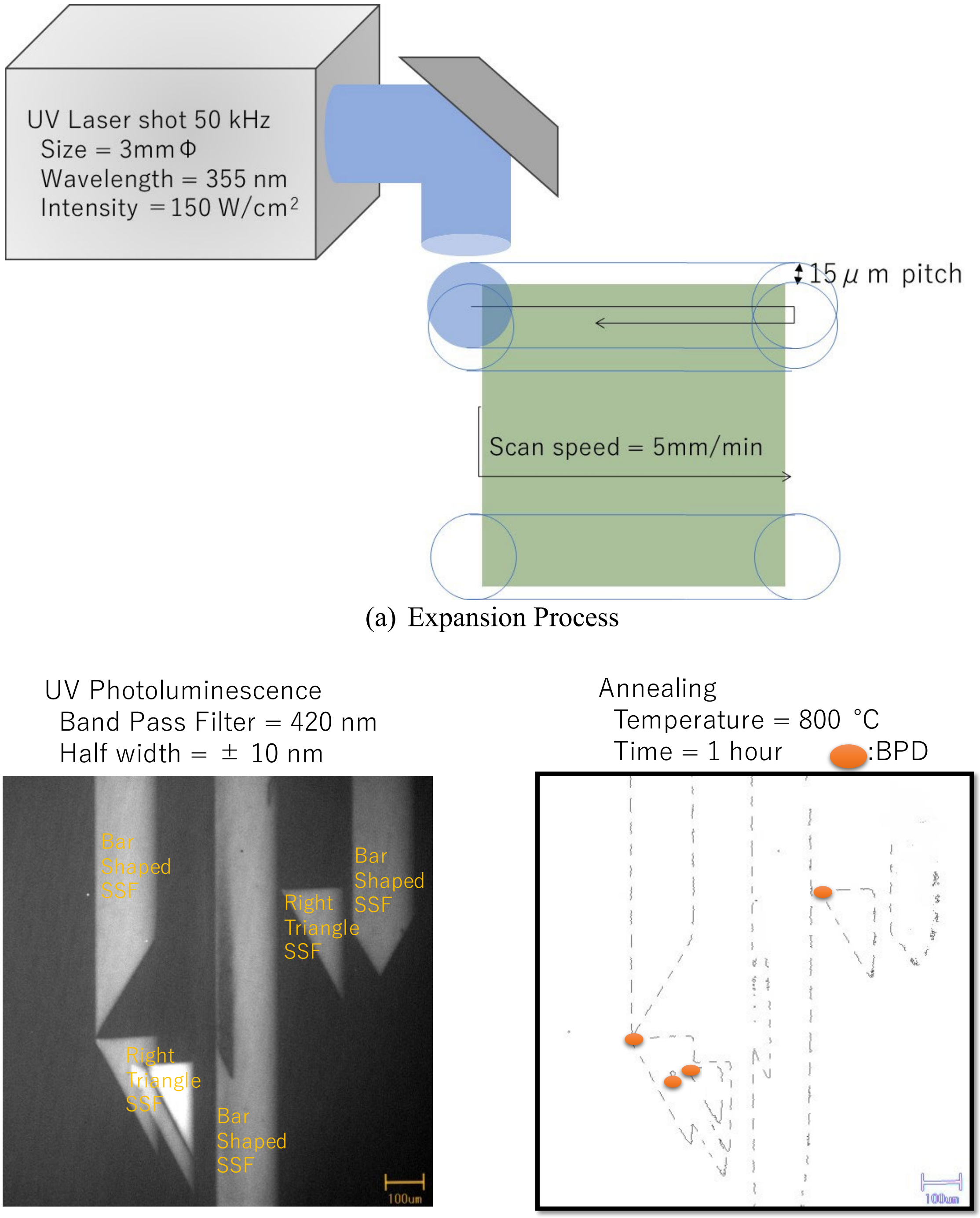
Introduction

Capital investment for mass production of SiC MOSFETs is underway around the world in preparation for the popularization and expansion of electric vehicles. The number of BPDs in the epilayer of 4H-SiC wafers has been greatly reduced by improving the manufacturing process, but on the other hand, 4H-SiC substrates still have a lot of BPD, so SiC Schottky diodes must be integrated into MOSFET modules to prevent forward bias degradation, which is costly. In the paper by Ishigaki et al. that investigated the forward bias degradation of approximately 10,000 SiC MOSFET modules, a 10 % increase in V(on) voltage was reported for 2-3% of the modules [1]. Hence, it is assumed that there was no problem in the 97-98 % of the 4H SiC wafer area where MOSFETs were fabricated where forward bias degradation did not occur.

UV-PL (UV Photoluminescence) [2], which is industrially implemented as a defect inspection method for 4H-SiC epi-wafers, cannot detect BPD converted to TED near the substrate-epi layer interface. The reason for this is that it is difficult to distinguish between substrate-derived TED and TED converted from BPD. On the other hand, Kallinger et al. showed that 1-SSF can be expanded from BPD at the wafer level as in electrical burn-in tests by applying optical stress to BPD in the epi-layer on a 4H-SiC substrate by irradiating it with a high UV laser [3]. Therefore, we propose an EVC method [4] that can also detect BPDs converted to TEDs in the wafer state using the UV-irradiation SSF expansion method.

When a 4H-SiC epi-wafer is irradiated with UV light, the SSF extends in the epilayer (Fig. 1 (a) Expansion Process), so both BPDs in the epilayer and BPDs converted to TEDs at the substrate-epilayer interface can be detected in the same way (Fig.1 (b) Visualization Process). After recording the coordinates of the malignant BPD at the expansion start point, the expanded SSF is contracted because leaving the expanded SSF in place will degrade its electrical characteristics (Fig.1 (c) Contraction Process).

In the previous report [5], we showed that one of the starting points of the SSF extended by UV irradiation was a BPD converted to TED at the epi-layer-substrate interface. In this paper, as a method to evaluate the accuracy of the EVC method, the reproducibility of SSF extended by forward biasing the PiN diode fabricated on a 4H-SiC wafer and SSF extended by UV irradiating the same PiN diode region were tested.



(a) Expansion Process

(b) Visualization Process

(c) Contraction Process

Fig. 1 The EVC (Expansion-Visualization-Contraction) method

Experiments and Results 1

In order to evaluate the accuracy of the EVC method, which predicts the expansion of the SSFs that causes forward voltage degradation, the same PiN diode device must be used for evaluation. However, the same PiN diode structure cannot be tested because UV light does not transmit the metal electrode when the flat electrode necessary for biasing is present. Therefore, an experiment was conducted in which the metal electrode was etched, the PiN structure was left intact, the SSF was contracted, and the same PiN diode region was irradiated with UV to expand the SSF again. The experimental flow was shown in Figure 2. If the SSF is missing, as in dotted line b, it means that the SSF expanded by forward bias cannot be matched with the SSF expanded by UV irradiation.

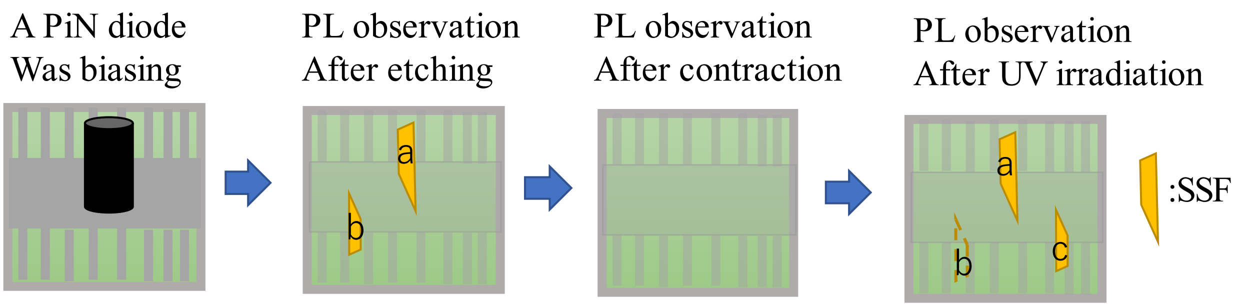


Fig.2 Experimental Flow

The sample investigated was a commercially available n-type 100 mm Φ 4H-SiC epi-wafer with a 4° off-cut angle, on which heavily nitrogen-doped buffer layer (0.5 μm, 1×10^{18} cm^{-3}) and lightly doped drift layer (5.4 μm, 6×10^{15} cm^{-3}) were epitaxially grown. The structure of the PiN diode used in our experiment was formed by doping aluminum (3×10^{20} cm^{-3}) on the Si face of the epi wafer. A nickel electrode was then formed on the entire backside of the wafer as Ohmic contacts. Finally, an aluminum electrode array of comb pattern was formed in half the area of the Si face surface wafer for forward bias stress.

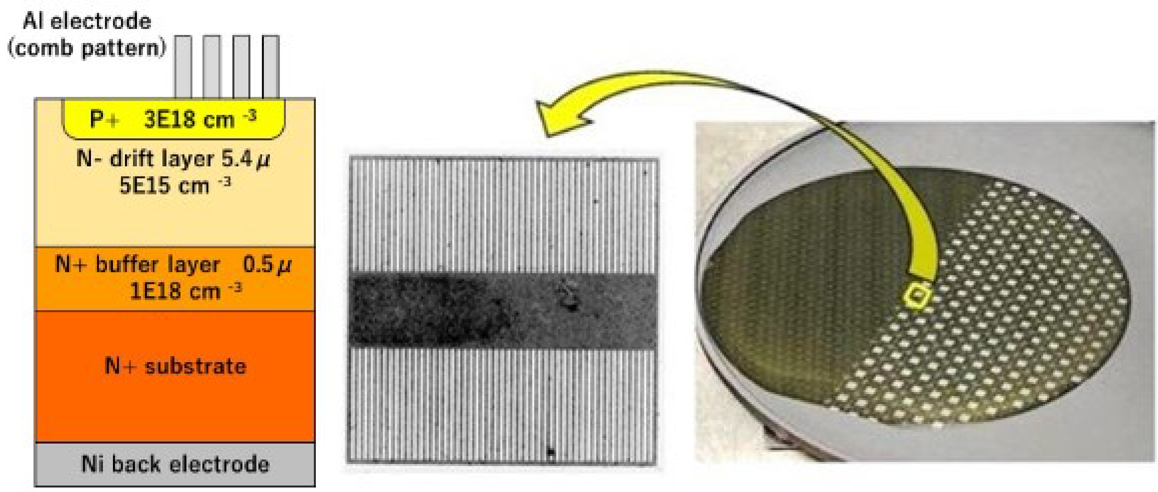


Fig.3 Schematic diagram of the PiN diode and photos of Al electrode pattern on SiC wafer

PiN diodes on the wafer were forward biased by accelerated pulsed current, and the PiN diode showed the emission with a blue wavelength according to the band gap (see Fig. 4 (a)). The SSF was observed by the UVPL method from the position of the Si(g) core partials visible through the gap between the comb line patterns (see Fig.4 (b)), which aligned with the step flow direction $[11\bar{2}0]$ of the SiC epi-wafer.

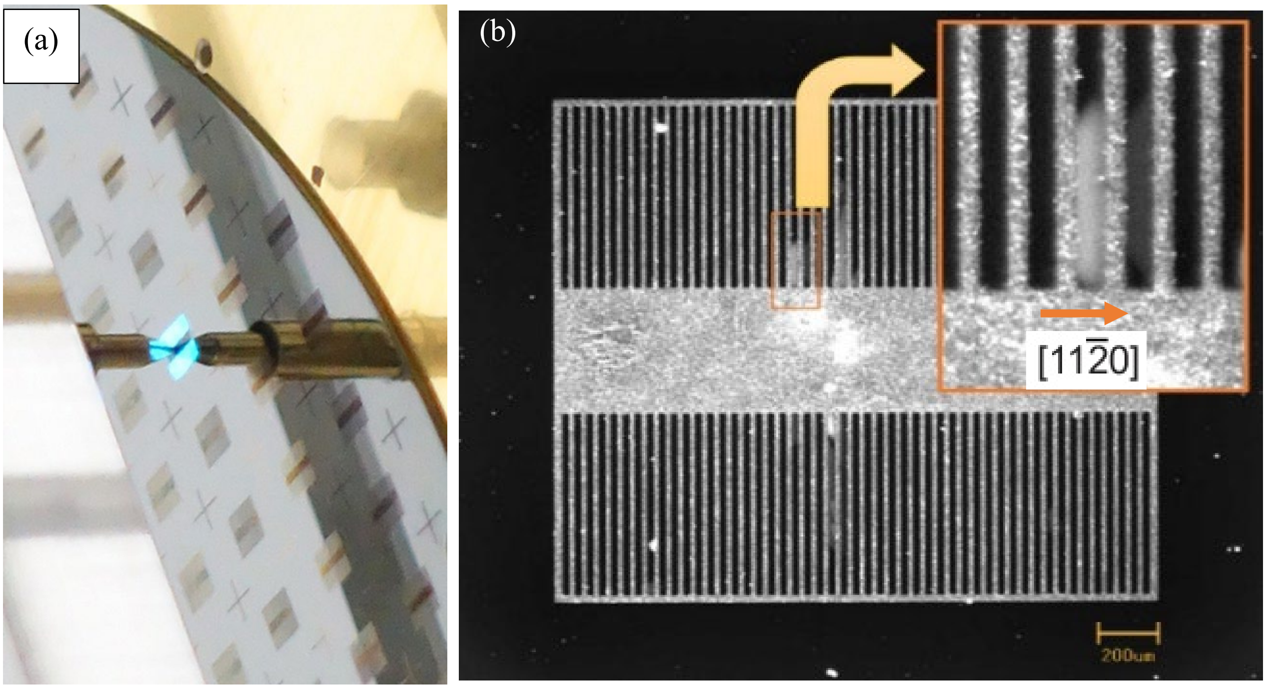


Fig. 4 (a) A light emitted PiN diode by biasing, (b) UVPL image of a PiN diode through BPF (420 nm) after forward biasing.

Not all BPDs expand at the same time, but the number of expanded SSFs increases over time under constant forward current conditions [6]. In this experiment, the current density was 400 A/cm2 for 8 minutes.

The aluminum electrode pattern of the PiN diode on the wafer was etched with hydrochloric acid, then thermal treated at 800°C for 1 hour to contract the SSF. The UV laser used was a Nd-YAG third harmonic (355nm), and the beam spot was adjusted to 3 mmΦ (143 W/cm^2) before irradiating the PiN diode area for 20 minutes without moving (Figure 5 (a)). Aluminum was removed, but the silicide remained, and the electrode pattern was visible (Fig.5 (b))

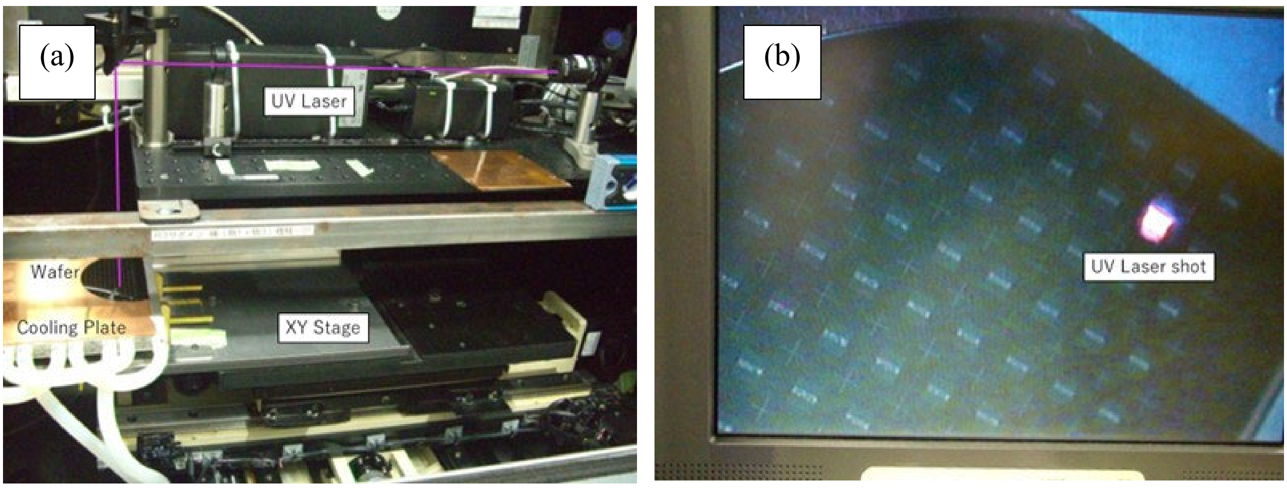
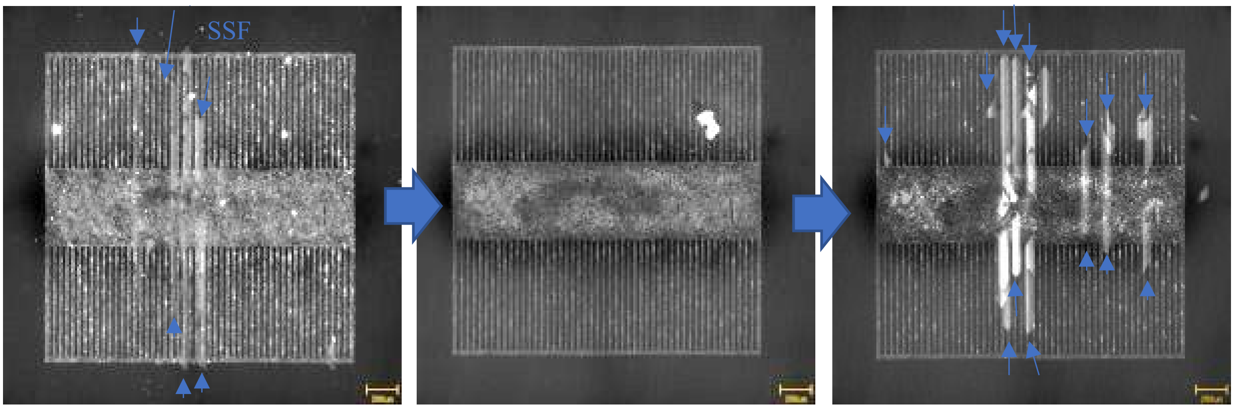


Fig. 5 (a) UV irradiation system (b) UV irradiation at a diode area

Next, three PL images (Fig. 6 (a) SSF expanded by forward biasing, (b) SSF contracted by thermal treatment, and (c) SSF expanded by UV irradiation) are shown as results. The bar shaped area indicated by the blue arrow was the extended SSFs.



(a) Forward Biasing (b) Contraction (c) UV Irradiation

Fig.6 PL images

SSFs extended by forward biasing and SSFs extended by UV irradiation resulted in very similar PL images. In this experiment, the objective was to capture the extended SSFs without omission by using excessive UV irradiation conditions. Therefore, The results of the SSF expansion were tabulated for each electrode window using the criteria in Table 1.

Table 1 Criterion

	Expanded SSF is present in electrode window	
Result	By UV irradiation	By forward biasing
match	present	present
match	absent	absent
latency	present	absent
missing	absent	present

Table 2 The EVC method accuracy

window	total	Result		
		match	latency	missing
Number	49	39	8	2

Excessive UV irradiation conditions were used in this experiment because the UV irradiation conditions that would be equivalent to 400 W/cm^2 of forward bias application were unknown. Since the objective is to capture the expanding SSF without omission, the accuracy of the EVC method was set to 100% minus the missing rate, (Eq.1).

EVC method Accuracy = (total – missing) / (total) (1)

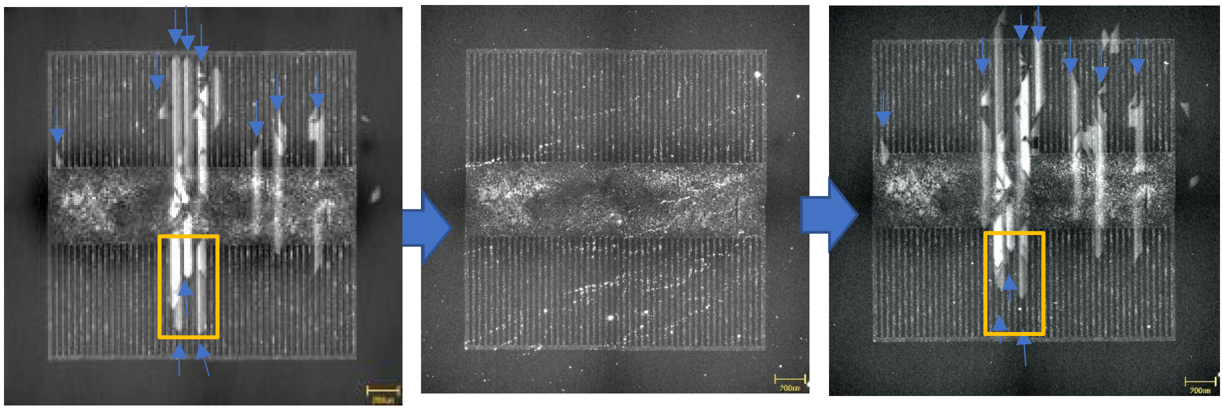
EVC method Accuracy was ９６% ≒ （４９-２）/４９.

Experiments and Results 2

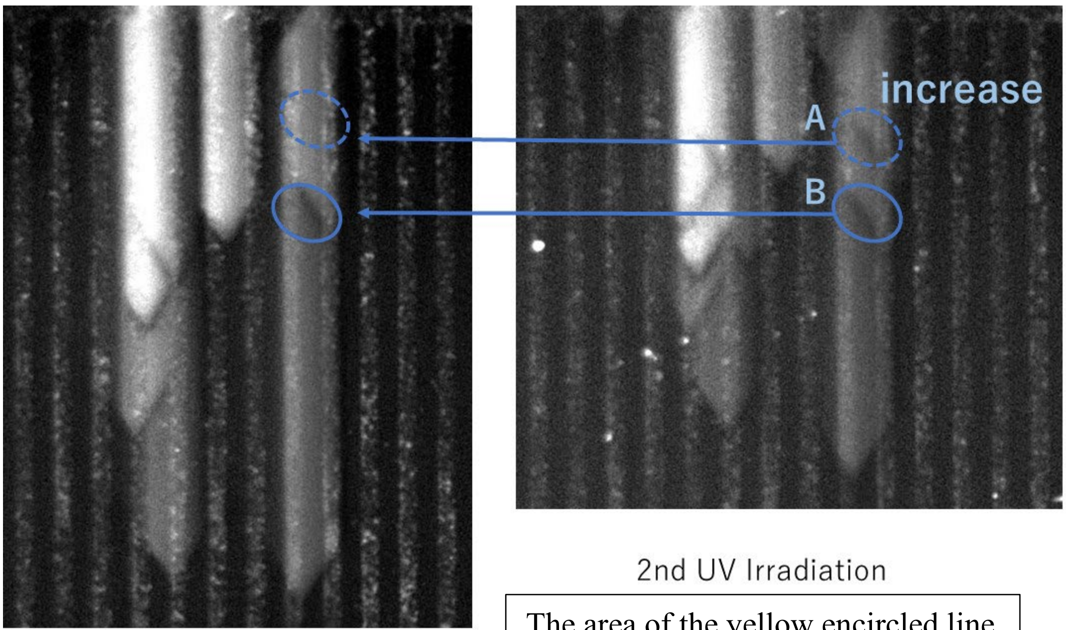
Next, we examined the causes of the missing. It is assumed that there are no BPDs that expand by forward biasing but not by UV irradiation. The reason for this is that the driving force for SSF expansion is the energy emitted when carriers recombine, and the strength of the recombination energy of injected carriers due to biasing and carriers due to UV irradiation is considered to be equivalent. This equivalence is due to the reported wavelength of electroluminescence and PL (photoluminescence) being the same at 390 nm. [7-8].

In this experiment, SSFs were expanded by first UV irradiation, followed by contraction by heat treatment (800°C, 1 hour), and then a second expansion by UV irradiation. Comparing SSFs from the first and second expansions, the counts per electrode window were 100% accurate.

On the other hand, when the SSF was contracted again and then expanded a second time by UV irradiation, the dislocation (dark line A) seen in a banded SSF increased (see Fig.7). The expansion and contraction of SSFs may have affected defects and impurities moved by dislocation core migration. The results confirmed that one dislocation was generated as an influence of the EVC method. The EVC method has a high accuracy, but in principle has a lower probability of being wrong.



1st UV Irradiation   2nd Contraction   2nd UV Irradiation



2nd UV Irradiation

1st UV Irradiation

The area of the yellow encircled line was expanded.

Fig. 7 UV-PL magnified Images Using Band pass filter 420nm

Summary

In this study, the produced PiN diode was forward biasing, the SSF was expanded, contracted by heat treatment, expanded again by UV irradiation, and contracted again by heat treatment. It was recognized that repeated expansion and contraction of the SSF would affect defects and impurities migrated by dislocation core migration. As a result, the EVC method may be misjudged, albeit with a small probability. However, the EVC method is effective as a screening method because it is the only method that can detect malignant BPD causing current-carrying degradation in the wafer state.

Acknowledgment

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