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On-resistance and Breakdown-Phenomenon Dependences on Threading Dislocations in Vertical p-n Junction Diodes

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Abstract

Through evaluations of p-n junction diodes fabricated on a high-quality GaN substrate by newly developed maskless 3D (M-3D) method with average TDD ≤ 4×10^5 cm^{-2}, roles of the threading dislocation on on-resistance (R_{on}) and breakdown phenomenon were examined. There found a clear correlation between the threading dislocations existing in the anode electrode region of the p-n diode and R_{on}. R_{on} tended to decrease as the number of dislocations decreased. On the other hand, there was no correlation between the catastrophic destruction point of the p-n diode by the breakdown and the position of the dislocation, which revealed that the dislocation was not the cause of promoting the catastrophic destruction of the p-n diode. This research provides guidelines for threading dislocation density (TDD) of the GaN substrates for fabrication of high performance vertical structure GaN power devices.

1. Introduction

Due to the excellent physical properties of GaN, vertical GaN power devices for have been widely studied. GaN substrates with a low TDD of about 3 x 10^6 cm^{-2} manufactured by the void assisted separation (VAS) method have been commercially available [1], and a very high breakdown voltage of 5.0 kV has been realized with a low R_{on} of 1.25 mΩ/cm^2 [2]. Recently, excellent quality GaN substrates with TDD ≤ 4 x 10^5 cm^{-2} have also become available by maskless 3D (M-3D) method from SCIOCS. In this study, the p-n diodes were fabricated on the M-3D substrate, and the influences of the number of threading dislocations below the anode on R_{on} and the breakdown phenomenon were studied.

2. Experimental

Figure 1 shows the structure of the p-n diode with approximate expected breakdown voltage (V_B) of 2 kV by simple Poisson's equation. The epitaxial layers were grown by metal-organic vapor-phase epitaxy (MOVPE) on the M-3D GaN substrate an using a multiple wafer reactor. The anode electrode diameter of the p-n diode used for evaluation was 60 µm. The mesa structure was formed by ICP-dry etching using Ar+CF_4 gas. For comparison, another etching method of damage-less photo-assisted electrochemical (PEC) etching was also evaluated. The etching solution was NaOH, and the details have been previously reported [3] [4].

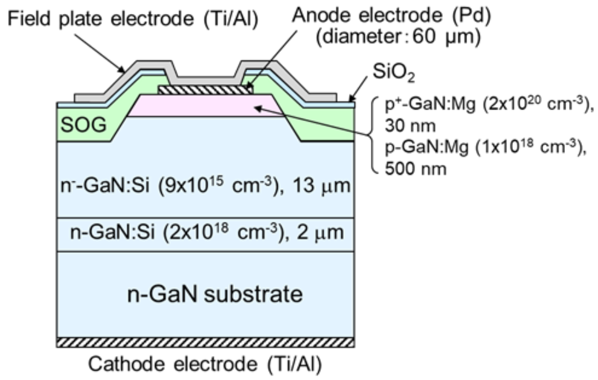

Fig. 1. Schematic structure of the vertical p-n junction GaN diode.

3. Results and Discussion

Figure 2 shows typical CL images of epitaxial layers grown on the M-3D and the VAS substrates. The low TDD achieved by the M-3D can be clearly seen. Figure 3 shows variations of R_{on} against the number of dislocations under the anode electrode for all of the measured p-n diodes. A positive

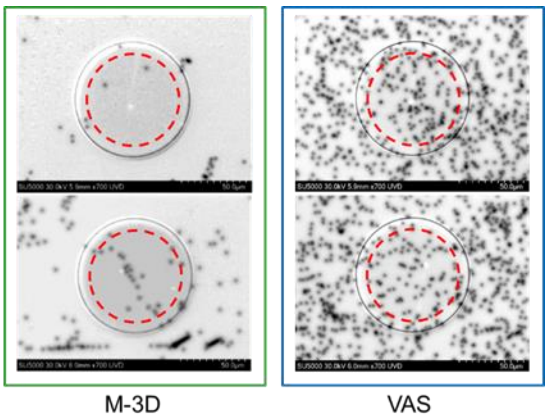

Fig. 2. Typical CL images of the GaN p-n junction diodes after formation of mesa structures. The red circles indicate areas of anode electrodes. The number of dislocations and their positions within the electrode area were recorded for all of the diodes fabricated in this study.

correlation between R_{on} and the number of dislocations was seen. The phenomena could be understood by the following discussion. It has been reported that the forward resistance of GaN p-n diodes could be reduced by conductivity modulation relating to the photon-recycling effect caused by radiative recombination of injected carriers [5]. However, the dislocations and their surrounding vacancies (seen as dark spots in Fig. 3) have been reported to be non-radiative centers [6], which should reduce the photon-recycling effect leading the lower conductivity modulation and the higher R_{on}.

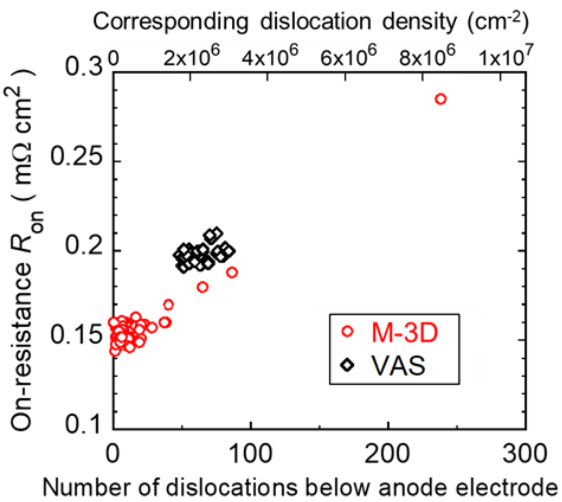

Fig. 3. On-resistance dependence on the number of dislocations below the anode electrode.

Figure 4 shows an optical image after the destruction by the breakdown at the reverse I-V measurement and the CL image after the mesa etching for the identical p-n diode. In the M-3D substrate, since the dislocation density was low, the destruction point of the p-n diodes could be clearly compared with the positions of the dislocations. It was found that the destruction point did not match the dislocations. The same results were found for almost all of the measured p-n diodes. In the begging of this study, ICP-dry etching was used for mesa etching. The dry etching damage at the mesa edge might cause the destruction regardless of the existence of dislocations. In order to clarify this doubt, another evaluation was performed on the p-n diodes fabricated by the damage-less PEC etching method. Figure 5 shows the optical image of the p-n diode after the destruction by the reverse I-V measurement and the CL image after the mesa etching by the PEC etching. The destruction point did not match the dislocations again as in the case of the ICP-dry etching. This result indicates that the dislocations have very little effect on the destruction of the p-n diode by the breakdown. Further investigation to find the cause of the destruction is required. Incidentally, the CL image of the PEC-etched surface was much brighter than that of the ICP-dry etched surface with damages; hence, the image of Fig. 5 (b) was captured with a less exposure compared to Fig.4 (b). This is the reason why the p-GaN region in Fig. 5 (b) looks dark.

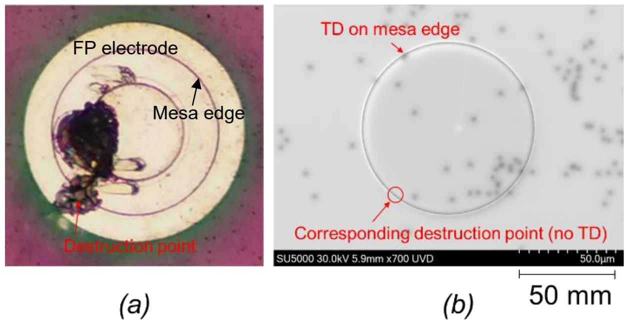

Fig. 4. (a) Optical image of a destroyed diode by reverse I-V measurements. (b) CL image of the diode after mesa etching. The destruction point did not match the dislocation.

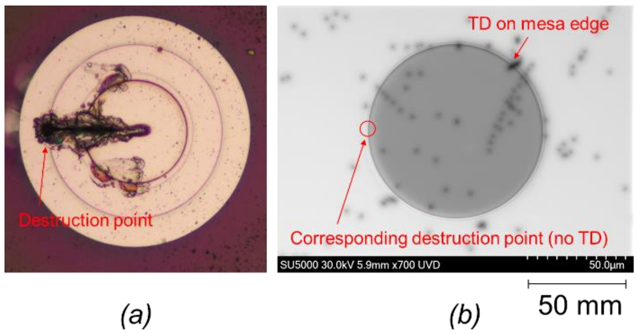

Fig. 5. (a) Optical image of a destroyed diode by reverse I-V measurements. (b) CL image of the diode after mesa etching by PEC etching. The destruction point did not match the dislocation.

4. Conclusions

The impact of threading dislocation on R_{on} and breakdown phenomenon was evaluated. A positive correlation between R_{on} and the number of dislocations was observed. On the other hand, the destruction point by the breakdown did not match the dislocations, which suggested that the dislocations had very little effect on the destruction of the p-n diode.

Acknowledgements

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