K-7-02
Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp489-490

High-Resolution Observation of In-Plane Carrier Concentration Nonuniformity in Vertical GaN p-n Diode Using Franz–Keldysh Effect and Avalanche Multiplication

Seiya Kawasaki[1], Hayata Fukushima[1], Shigeyosihi Usami[1], Yuto Ando[1], Atsushi Tanaka[2,3], Manato Deki[3], Maki Kushimoto[1], Shugo Nitta[3], Yoshio Honda[3] and Hiroshi Amano[2,3,4,5]

[1] Dept. of Electronics, Nagoya Univ., Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
Phone: +81-52-789-5275, E-mail: s.kawasaki@nagoya-u.jp
[2] NIMS, 1-2-1, Sengen, Tsukuba, 305-0044, Japan
[3] IMaSS, Nagoya Univ., Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
[4] VBL, Nagoya Univ., Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
[5] Akasaki R.C., Nagoya Univ., Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Abstract

We report a novel observation method for in-plane carrier concentration nonuniformity: the optical beam induced current (OBIC) measurement by sub-bandgap light using the Franz–Keldysh effect and avalanche multiplication. When a GaN p-n diode was observed by this method, an in-plane mapping image reflecting the difference in in-plane photocurrent intensity was obtained. We found that it shows the difference in the multiplication factor and this is caused by carrier concentration nonuniformity, which is of 10^{14}cm^{-3} order by calculation. This indicates that this method has a high resolution.

1. Introduction

GaN has attracted much attention as a next–generation material for power devices because of its high critical electric field. There have been many reports on GaN vertical power devices. Recently, a simple structure with a uniform electric field distribution was reported for a GaN vertical p-n diode (PND) [1], [2] that shows excellent reverse *I*–*V* characteristics. However, the luminescence at breakdown has appearance of a stripe [1] or dots [2], suggesting in-plane minute carrier concentration nonuniformity. To discuss the theoretical limit of the breakdown voltage of a GaN PND, it is necessary to clarify how much fluctuation of the carrier concentration occurs. In this study, we propose optical beam induced current (OBIC) measurement with sub-bandgap light using the Franz–Keldysh effect (F–K effect) [3], [4] and avalanche multiplication as a new observation method of carrier concentration nonuniformity. In a PND, the absorption of sub-bandgap light owing to the F–K effect occurs in a high-electric-field region around p-n junction, so it is expected that the information (electric field or carrier concentration) can be obtained as photocurrent. In addition, the photocarrier multiplication factor is sensitive to the electric field distribution. The electric field distribution is determined by the carrier concentration. Therefore, we can determine the carrier concentration from the multiplication factor. For this reason, we can observe carrier concentration nonuniformity directly by combining these phenomena.

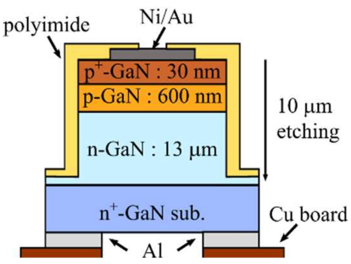

Fig. 1 Schematic diagram of p-n diode.

2. Experiment

Fig. 1 shows a schematic diagram of the PND that we fabricated. We utilized a vertical deep mesa structure for the edge termination [1]. It consists of a p$^+$-layer (Mg: >2×10^{20}cm^{-3}, 30 nm), p-layer (Mg: 2×10^{19}cm^{-3}, 600 nm), and n-layer (Si: 2.4×10^{16} cm^{-3}, 13 μm) grown by metal-organic vapor phase epitaxy on an n$^+$-GaN free-standing substrate fabricated by hydride vapor phase epitaxy. The carbon concentration in the n-layer is 1.5×10^{16} cm^{-3} and the net donor concentration obtained by *C*–*V* measurement is 2.1×10^{16} cm^{-3}. The vertical deep mesa structure is fabricated by inductive coupled plasma–reactive ion etching. The etching depth is 10 μm and the mesa diameter is 540 μm. To passivate the sidewall surface, it is coated with 3-μm-thick polyimide. Fig. 2 shows a schematic of the measurement system. We used emission microscopy (PHEMOS-1000, Hamamatsu Photonics) for the OBIC measurement. The wavelength of the scanning laser is 405 nm, at which the F–K effect can be observed in the GaN PND [5]. The scanning laser enters from back (substrate side) of the PND with an applied voltage close to the breakdown voltage, and the in-plane mapping image (OBIC image) is obtained as a grayscale image corresponding to the in-plane photocurrent intensity distribution. After that, the reverse *I*–*V* characteristics with photon excitation by the 405 nm laser are measured without scanning at a bright point

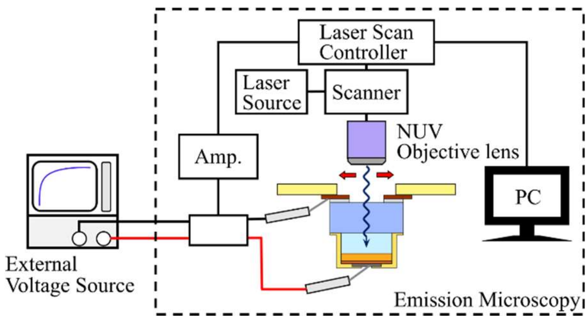

Fig. 2 Schematic of the OBIC measurement system.

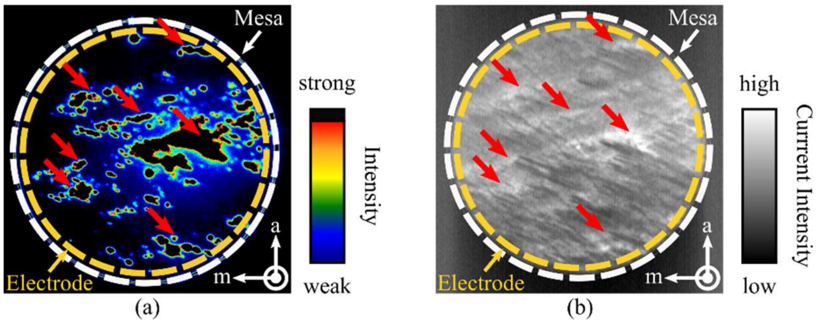

Fig. 3 (a) Emission microscopy image at −827 V and (b) OBIC image at −812 V. The mesa diameter is 540 μm and the electrode diameter is 500 μm. Red arrows show corresponding points on the emission microscopy image and the OBIC image.

and a dark point, as shown in Fig. 3, and the voltage dependence of the multiplication factor at each point is obtained.

3. Results and Consideration

Fig. 3(a) shows an emission microscopy image of the PND at the breakdown voltage and Fig. 3(b) shows its OBIC image. The bright region in the OBIC image shows good agreement with the emission pattern. Fig. 4 shows the voltage dependence of the multiplication factor at the bright point and dark point shown in Fig. 3(b). The multiplication factor is defined as the ratio of the measured photocurrent to the calculated F–K-effect-induced photocurrent, $M = I/I_{FK}$. The two multiplication curves are very similar, although the curves show slightly different reverse bias voltage above 700 V. This shows the slight difference in the electric field distribution between the two points. In the vertical deep mesa PND, electric field crowding does not occur [1] so it seems that this difference indicates in-plane carrier concentration nonuniformity. The multiplication factor can be calculated using the ionization integral [6]. In the p^+-n one-sided abrupt-junction diode, the measured multiplication factor under the photon-excitation-induced F–K effect can approximate the electron-initiated multiplication factor, $M \approx M_n$. To calculate M_n, the electron and hole impact ionization coefficients, α_n and α_p, respectively, are necessary. There have been several reports on their values in GaN [7], [8]. However, a precise value is still to be determined; therefore, first, α_n and α_p were determined by fitting the experiment data at the bright point (red marks shown in Fig. 4) with Chynoweth's equation [9]. The net donor concentration used was 2.10×10^{16} cm^{-3}, obtained from *C–V* measurement. The result of the fitting is shown in Fig. 4. The calculated curve (red dashed line) shows good agreement with experimental results and $\alpha_n = 1.86\times10^6\cdot\exp\{(-1.13\times10^7/E)\}$ cm^{-1} and $\alpha_p = 2.35\times10^6\cdot\exp\{(-1.55\times10^7/E)\}$ cm^{-1} are obtained, where E is the electric field. Then, N_d is determined by fitting the experiment data at the dark point (blue marks shown in Fig. 4) using these α_n and α_p. The multiplication curve calculated using $N_d = 2.07\times10^{16}$ cm^{-3} shows good agreement (blue dashed line shown in Fig. 4) with experimental results. This means that the difference between these multiplication curves at each point can be explained by net donor concentration nonuniformity, which is of 180^{14} cm^{-3} order, and the luminescence variation in the previous report [1], [2] can also be explained by this slight nonuniformity.

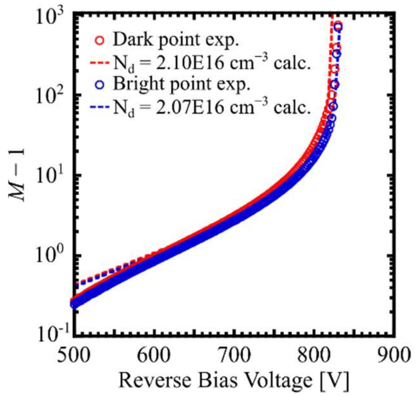

Fig. 4 Voltage dependence of multiplication factor at bright point (red) and dark point (blue).

4. Conclusions

In this study, we proposed OBIC measurement making use of a combination of the F–K effect and avalanche multiplication as a method of observing the carrier concentration nonuniformity in a vertical GaN PND. The OBIC image showed good agreement with the emission microscopy image and reflected the difference in the in-plane multiplication factor. This difference can be explained by the net donor concentration nonuniformity, which is of 10^{14} cm^{-3} order as determined using the ionization integral, and it means the luminescence variation at breakdown also occurred as a result of this slight carrier concentration nonuniformity. This result indicates that this method enables a high resolution of 10^{14} cm^{-3} order in the observation of carrier concentration nonuniformity in a GaN vertical PND.

Acknowledgements

This work was supported by MEXT "Program for research and development of next-generation semiconductor to energy-saving society."

References

[1] H. Fukushima *et al.*, Appl. Phys. Express, **12**, (2019) 026502.
[2] T. Maeda *et al.*, IEDM Tech. Dig., (2018) p. 30.1.1.
[3] W. Franz, Z. Naturfosch., **13(a)**, (1958) 484.
[4] L. V. Keldysh, Sov. Phys. -JETP, **34(7)**, (1958) 5.
[5] T. Maeda *et al.*, Appl. Phys. Lett., **112**, (2018) 252104.
[6] B. J. Baliga, *Fundamentals of Power Semiconductor Devices*, (Springer, Raleigh, NC, 2008), p. 91.
[7] H. Oguzman, J. Appl. Phys., **81**, (1997) 7827.
[8] L. Cao *et al.*, Appl. Phys. Lett., **112**, (2018) 262103.
[9] A. G. Chynoweth, Phys. Rev., **109**, (1957) 5.