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Measurement of Avalanche Multiplication Factor in GaN p-n Junction Diode Using Sub-Bandgap Light Absorption Due to Franz-Keldysh Effect

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Abstract

The photocurrents in a homoepitaxial GaN p-n junction diode under sub-bandgap light illumination were investigated. Voltage and wavelength dependences were quantitatively explained by the light absorption due to the Franz-Keldysh effect under reverse voltages up to 200 V. For higher reserve voltages of 250 V, avalanche multiplication was observed. The multiplication factor was successfully obtained up to the breakdown voltage.

1. Introduction

A semiconductor under a high electric field exhibits sub-bandgap optical absorption. This is known as the Franz-Keldysh (FK) effect [1, 2]. GaN has attracted much attention as a material for next-generation power devices, since it has a high breakdown electric field (> 3 MV/cm). We have observed the FK effect in GaN Schottky barrier diodes (SBDs) and p-n junction diodes (PNDs) via photocurrents induced by the sub-bandgap light [3, 4]. The calculated curves with consideration of the light absorption due to the FK effect showed excellent agreements with the experimental curves in the voltage range of 0-200 V.

In this study, we investigated the photocurrent under higher reverse voltages of 200-420 V. We observed rapid increases in the photocurrents over 250 V. The increases reflected avalanche multiplication in the depletion region. By comparing the calculated FK-induced photocurrents and the measured photocurrents, the avalanche multiplication factors were successfully extracted.

2. Experiments, Results and Discussions

Figure 1 shows the schematic cross section of the GaN PNDs. The device consists of a p^+-layer, a p-layer, and an n-layer grown on a GaN bulk substrate. The Mg concentration in the p-layer was 3×10^{17} cm^{-3} and the Si concentration in the n-layer was 7×10^{16} cm^{-3}. The epilayer was etched by ICP-RIE and mesa structures were formed.

The device showed high breakdown voltages (~420 V), low leakage current, and a sufficient avalanche capability; the catastrophic breakdown was not observed and the same characteristic can be reproduced many times. However, the electroluminescence was observed in the edge of the mesa when the breakdown occurred in the device, which indicated that the device was not free from an electric field crowding.

Figure 2 shows the reverse current-voltage characteristics in the GaN PND under monochromatic light illumination (with a linewidth of 5 nm). The wavelength of the light was varied in the range of 390-410 nm. The sub-bandgap light that penetrated into GaN was reflected by the back-side cathode, and could reach the p-n junction from the back side. Under high reverse bias voltages, the photocurrents were observed. The photocurrents increased with the reverse bias voltages, and the increases were more striking as the wavelength approached the absorption edge (365 nm, 3.4 eV).

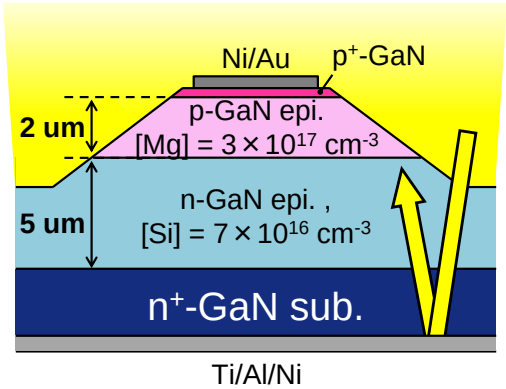

Fig. 1. Schematic cross-section of the GaN PND. The light that entered the GaN layer was reflected and could reach the p-n junction from the back side.

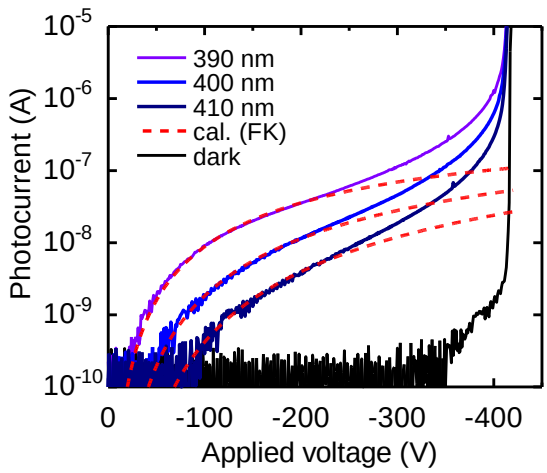

Fig. 2. Voltage dependence of the measured photocurrents for the wavelengths of 390, 400, and 410 nm (solid lines). The calculated curves with consideration of the light absorption due to the FK effect (red broken lines) show excellent agreements with the measured curves in lower reverse bias voltages range than 200 V.

We calculated the photocurrent induced by the FK effect in the GaN PND. The absorption coefficient in a direct bandgap semiconductor under an electric field was given by Aspnes [5]. In the calculation, the reduced effective mass parallel to the direction of the applied electric field strongly impacts on the electric-field dependence of the absorption coefficient, and the value of $\mu^{\parallel} = 0.16m_0$ calculated from the electron and hole effective masses [6] was used. The calculated absorption coefficient was described in [3].

Figure 3 shows the distributions of the absorption coefficient in the GaN PND under a reverse bias voltage of 200 V. The absorption coefficient is large near the p-n junction interface, where the electric field is strong. The photocurrent induced by the FK effect can be calculated by considering the amount of the light absorption in the depletion layer.

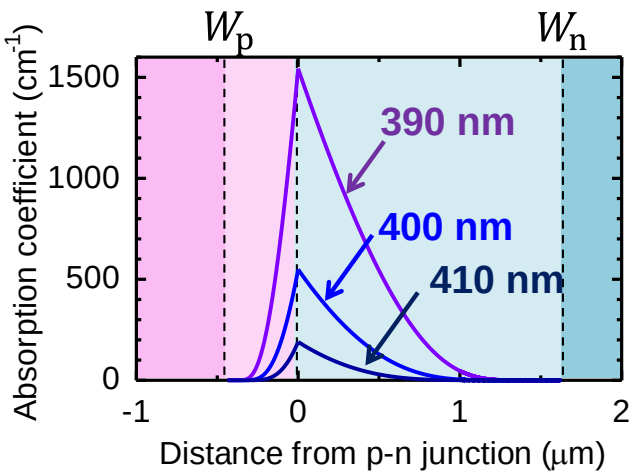

Fig. 3. The distributions of the absorption coefficients for the wavelengths of 390, 400, and 410 nm in the GaN PND under the reverse bias voltage of 200 V.

The calculated photocurrents induced by the FK effect for 390, 400, and 410 nm are shown in Fig. 2 as red broken lines. The calculated photocurrents due to the FK effect (I_{FK}) showed excellent agreements with the measured photocurrents (I_{m}) in the range of 0-200 V. Under a higher voltage than 250 V, the measured photocurrents significantly increased and became much larger than the calculated curves. These significant increases were considered to originate in an avalanche multiplication due to the impact ionizations of electrons and holes in the depletion layer.

We extracted the multiplication factor as the ratio of the measured photocurrent to the calculated FK-induced photocurrent ($M = I_{\mathrm{m}}/I_{\mathrm{FK}}$) for each wavelength. Figure 4 shows the voltage dependences of the multiplication factors obtained from the photocurrents for 390, 400, and 410 nm. Although the photocurrents became larger as the wavelengths approached the GaN absorption edge, all the multiplication factors for 390, 400, and 410 nm were the same.

The multiplication factor depends on the position where the carriers are generated, since there is a difference between the impact ionization of an electron and a hole. In this study, the positions where the electron-hole pairs were generated were localized near the p-n junction interface for all the wavelengths, as shown in Fig. 3. Therefore, these results are reasonable. The extracted multiplication factors increased with increases in the reverse voltages, and approached the infinity.

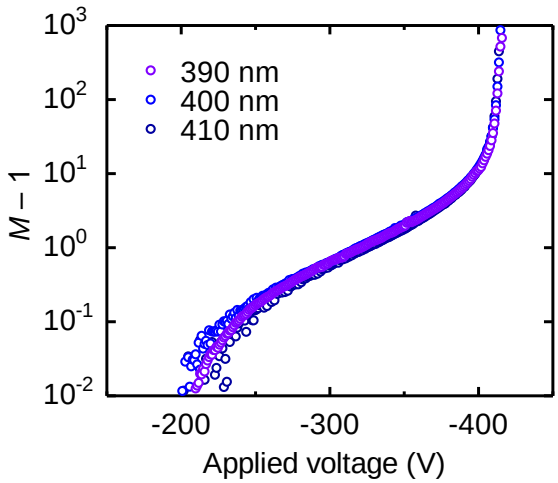

Fig. 4. Voltage dependence of the multiplication factor in the GaN PND extracted as $M = I_{\mathrm{m}}/I_{\mathrm{FK}}$. All the multiplication factors for the wavelengths of 390, 400, and 410 nm were the same.

3. Conclusions

The avalanche multiplication factors in GaN PND were extracted as the ratios of the measured photocurrents to the calculated FK-induced photocurrents. The avalanche multiplication factors were obtained from the photocurrents for the wavelengths of 390, 400, and 410 nm. They did not depend on the wavelengths, reflecting the localized electron-hole pairs generation near the p-n junction interface for all the wavelengths.

Compared with above-bandgap photoexcitation, the sub-bandgap photoexcitation due to the FK effect has a unique feature; the electron-hole-pair generation selectively occurs at the high-electric-field region. The sub-bandgap photoexcitation measurements are considered to be useful for understanding the avalanche breakdown characteristics.

Acknowledgements

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