Scanning internal photoemission microscopy measurements of n-GaN Schottky contacts under applying voltage

Kenji Shiojima1, Masataka Maeda1, and Tomoyoshi Mishima2
1Graduate School of Electrical and Electronics Engineering, University of Fukui, Fukui 910-8507, Japan
2Hosei University, Koganei, Tokyo 184-0003, Japan
E-mail: shiojima@u-fukui.ac.jp
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We applied scanning internal photoemission microscopy (SIPM) to characterize the degradation of GaN Schottky contacts formed on a thick n-GaN layer grown on a freestanding GaN substrate by in situ applying reverse bias voltage ($V_{bias}$) down to −45 V. For most of the contacts, uniform distribution of the photocurrent was observed over the electrode with the visible lasers. Irregular-shape regions with 5%–25% larger photocurrent appeared with the near UV laser by applying $V_{bias}$, but the $I$–$V$ characteristics were stable. On the other hand, for the contacts with a slightly larger reverse current, the photocurrent distribution was also uniform at $V_{bias} = 0$ V, but over $V_{bias} = −36$ V, the photocurrent was intensively increased at small spots. After the SIPM measurements, the $I$–$V$ characteristics became leaky, and the same spots were observed in the microscope image. These results indicate that SIPM is useful for in situ monitoring of the initial stage of the degradation under applying reverse bias voltage. © 2019 The Japan Society of Applied Physics

1. Introduction

GaN based electron devices have been employed in a variety of commercial RF-power-amplifier applications,1–5 because of their characteristics of high-breakdown field and high electron velocity. Recently, the development of high-quality freestanding GaN substrates6–8 has accelerated the development of GaN power switching devices. Freestanding GaN substrates allow epitaxial growth of the thick drift layers with low dislocation density, which is indispensable for the diodes to achieve high-breakdown voltages. To achieve GaN Schottky and p–n diodes with very high-breakdown voltages (over 1 kV),6–11 a free carrier concentration of $1 \times 10^{16}$ cm$^{-3}$ or lower is required in the n-GaN thick drift layer. Freestanding GaN substrates allow the homo-epitaxial growth of thick GaN layers without wafer curvature or cracks, which have been a typical problem for lattice-mismatched substrates. However, controlling the carrier concentration in the thick drift layer is still difficult, and the effects of residual C acceptors and other point defects must be taken into account.12,13 We also reported uniformity of carrier concentration in conjunction with surface morphology over the wafer.14 The surface off-angle of the GaN substrate affected incorporated C concentration during the growth, which resulted in uniformity of the carrier compensation in a low-carrier n-GaN drift layer.15

On the other hand, we have developed a new two-dimensional mapping characterization termed scanning internal photoemission microscopy (SIPM) to verify the electrical inhomogeneity of metal–semiconductor (M/S) interfaces.16,17 Thus far, we have demonstrated the mapping of characteristics in interfacial reactions, degradation under applying voltage stress and surface damage in Si, GaAs, GaN, IGZO, and SiC Schottky contacts.18–25 We also demonstrated the characterization of crystal quality of wafer-bonded Si/SiC heterointerfaces.26 We confirmed that macroscopic mapping investigation for the entire electrodes by using this technique is a powerful tool for developing high-power wide-bandgap electron devices.

We came up with applying SIPM to characterize the initial stage of the degradation of the Schottky diodes that were formed on a low-carrier thick n-GaN layer grown on a freestanding GaN substrate. In this paper, we propose two new functions in the SIPM measurement. We have been using visible lights for probing M/S interfaces. We adopted near ultra violet (NUV) light, which can enable us to observe not only M/S interfaces but also depletion layers. In addition, we applied reverse bias voltage during the measurements, which can provide in situ observation of the degradation. In our previous report, we conducted demonstration of SIPM measurements for GaN Schottky contacts using the NUV light in Ref. 27. In this paper, we report in more detail the photocurrent transport mechanism including spectroscopic analysis associated with the bias voltage.

2. Device fabrication and measurement

Figure 1 shows the device structure of the Ni/n-GaN Schottky contact. Freestanding GaN substrates were prepared by the unique void-assisted separation (VAS) technology of SCIOCS, which is based on the hydride vapor phase epitaxy
The dislocation density was $3 \times 10^6 \text{cm}^{-2}$, and the donor concentration was $2 \times 10^{18} \text{cm}^{-3}$ in the substrates. We grew 2 $\mu$m n-GaN layers, doped with $2 \times 10^{18} \text{cm}^{-3}$ silicon, as an access region, followed by 12 $\mu$m thick n-GaN drift layers, where the target free carrier density was controlled to $1 \times 10^{16} \text{cm}^{-3}$. After a HCl surface treatment, circular 100 nm thick Ni Schottky contacts (200 $\mu$m in diameter) were deposited by the electron beam evaporation. After that, InGa ohmic contacts were deposited on the back surface.

We measured $I$–$V$ characteristics of the fabricated devices by using a semiconductor parameter analyzer (HP4142B). We determined the Schottky barrier height ($q\phi_B$) and an ideality factor ($n$-value) by using the thermionic emission model:

$$J = A^* T^2 \exp\left(-\frac{q\phi_B}{kT}\right) \left[\exp\left(\frac{qV}{nkT}\right) - 1\right],$$

where $A^*$ is the effective Richardson constant (26.4 A cm$^{-2}$ K$^{-2}$ for n-GaN based on $A^* = 4\pi m^* q k^2 / h^3$ and $m^* = 0.22 m_0$), $T$ is the temperature, $q$ is the electron charge, $k$ is the Boltzmann constant, and $V$ is the applied voltage.

Prior to the SIPM measurements, we conducted conventional photoresponse (PR) measurements where a photon energy ($h\nu$) was continuously scanned from 1.2 to 4.0 eV, in order to confirm the shape of the PR spectrum of the Ni/n-GaN contact. In the PR measurements, a monochromatic light from a monochrometer was used and irradiated to the entire contact area. As shown in Fig. 2, when a monochromatic light with $h\nu$ that is greater than $q\phi_B$ is incident on a metal/n-GaN interface, carriers in the metal can surmount the Schottky barrier and a photocurrent may be generated, which is called the internal photoemission effect. The relationship between $h\nu$ and the photoyield ($Y$), which corresponds to the photocurrent per the number of incident photon, is given by Fowler’s equation:

$$Y^{1/2} \propto h\nu - q\phi_B.$$  

The $q\phi_B$ can be determined from Eq. (2).

In the SIPM measurements, we focused and scanned the laser beam over the interface of the electrode to obtain a two-dimensional image of $Y$. One mapping measurement takes about 1 h. The $Y$ imaging measurements were repeated with different wavelengths to obtain an estimate of $q\phi_B$ by Eq. (2). In this case, all the information is from the M/S interface.
When $h\nu$ is close to the fundamental absorption edge, a large photocurrent always flows because of the generation of electron–hole pairs as in a solar cell, and the linear relationship that is defined in Eq. (2) no longer holds. We can observe both M/S interface and depletion region. In this SIPM study, we used red ($\lambda_1 = 659\text{ nm}$, $h\nu_1 = 1.88\text{ eV}$) green ($\lambda_2 = 517\text{ nm}$, $h\nu_2 = 2.40\text{ eV}$) and blue ($\lambda_3 = 447\text{ nm}$, $h\nu_3 = 2.77\text{ eV}$) light lasers for the internal photoemission, and NUV ($\lambda_4 = 375\text{ nm}$, $h\nu_4 = 3.31\text{ eV}$) for the fundamental absorption. The beam spot diameter was estimated as 2 $\mu$m. In addition, the SIPM measurements were conducted with applying reverse bias voltage ($V_{\text{bias}}$) down to $-45\text{ V}$ to the contact for the in situ observation of the degradation.

3. Results and discussion

3.1. Basic electrical characteristics

Figures 3(a) and 3(b) show the typical forward and reverse $I$–$V$ characteristics in a semilog-plot, respectively. We measured about 100 electrodes, and the $I$–$V$ characteristics are divided into two groups. Most of the electrode ($>95\%$), termed Dot 1, exhibited a linear semilog-$I$–$V$ relationship under the forward voltage between $+0.3$ and $+0.8\text{ V}$, and the reverse biased current below the noise floor of 0.1 pA down to $V = -50\text{ V}$. According to the thermionic emission model, the inserted table shows obtained $q\phi_B$ values and $n$-values from the forward $I$–$V$ curves. Dot 1 showed a large $q\phi_B$ value of 1.16 and a small $n$-value of 1.04. Catastrophic breakdown occurred around $V = -500\text{ V}$ at the edge of the electrode, because of no edge termination in these devices. Comparing with the experimental results which we have reported so far in Ref. 11, reasonable $I$–$V$ characteristics were obtained. On the other hand, small number of electrode ($<5\%$), termed Dot 2, exhibited almost the same forward $I$–$V$ characteristics as Dot 1 ($q\phi_B = 1.12$ and $n$-value $= 1.10$), but the reverse biased currents gradually increased up to 10 pA at $V = -50\text{ V}$ without breakdown.

Conventional PR measurements were conducted, where a monochromatic light was illuminated over the entire contact for Dot 1. Figure 4 shows the entire PR spectra under application of different $V_{\text{bias}}$ from 0 to $-45\text{ V}$. As mentioned in Sect. 2, the square root of $Y$ linearly increased up to approximately $3.2\text{ eV}$. We noticed that the PR spectra are independent of the $V_{\text{bias}}$ values in this $h\nu$ range. It is likely because excited electrons in the vicinity of the interface on the metal side can surmount the Schottky barrier and contribute to the photocurrent. We assumed that the $Y$ obeys Eq. (2). Therefore, the values of $\nu_\nu$ were obtained to be 1.20 eV, which is close to the $q\phi_B$ value obtained from the $I$–$V$ measurement. $Y$ steeply increased from approximately $h\nu = 3.2\text{ eV}$; then, when $h\nu$ was larger than 3.3 eV, $Y$ dramatically decreased because of the fundamental absorption in the GaN epitaxial-layer and substrate as explained in Sect. 2. Even though $h\nu$ is slightly smaller than $E_g$, it can be considered that the excitation is possible via impurities and excitons. In this higher $h\nu$ range, the PR signal significantly increased as $V_{\text{bias}}$ decreased. We speculate that the depletion layer width became wider under large $|V_{\text{bias}}|$, and the number of electron–hole pairs which can contribute photocurrent increased. Therefore, we confirmed that we can investigate both M/S interface and the depletion layer in this higher $h\nu$ range. Basically, the same PR results were obtained from Dot 2. Judging from these results, we can estimate that the SIPM results with the red, green, and blue lasers are based on the internal photoemission, and that with the NUV laser includes the effect of the fundamental absorption.
3.2. Mapping characterization

Figure 5 shows typical \( Y \) maps measured with the (a) red, (b) green, (c) blue, (d) NUV lasers and (e) \( q_B \) maps of Dot 1 when \( V_{\text{bias}} = 0 \) V and \( V_{\text{bias}} = -45 \) V. In the \( Y \) maps with the visible lasers, uniform distribution of the photocurrent was observed over the electrode. In the \( q_B \) map calculated from these \( Y \) maps, uniform distribution was obtained as well. As expected in the PR results, the \( Y \) signals are independent of \( V_{\text{bias}} \). The averaged \( q_B \) value is 1.24 eV. We confirmed that our device fabrication process provided properly uniform M/S interfaces. On the other hand, as for the NUV map, the \( Y \) intensity increased from \( V_{\text{bias}} = 0 \) V to \( V_{\text{bias}} = -45 \) V as expected in the PR results. In addition, irregular-shape regions with 5%–25% larger \( Y \) appeared by applying \( V_{\text{bias}} \).

We also conducted the SIPM measurements with the NUV laser with changing \( V_{\text{bias}} \) for more detailed investigation. As shown in Fig. 6, the number and area of such regions increased as \( V_{\text{bias}} \) decreased. It can be considered that this inhomogeneity is located in the semiconductor side of the M/S interface. The origin of the inhomogeneity is not clear at this moment, but cluster of the threading dislocations may be possible. The \( I-V \) curves are the same before and after the SIPM measurements, because the applied \( |V_{\text{bias}}| \) is much smaller than the typical catastrophic breakdown voltage of \(|-500| \) V. Even though the inhomogeneity existed, Dot 1 was stable.

We conducted the SIPM measurements for Dot 2 in the same manner for Dot 1. Basically, the same uniform results were obtained with the visible lasers as those of Dot 1. However, during the NUV measurement with changing \( V_{\text{bias}} \), two spots appeared within the large \( Y \) regions at \( V_{\text{bias}} = -36 \) V as shown in Fig. 7. The maximum intensity of \( Y \) at the spots is more than one-order-of-magnitude larger than that of the surrounding region. It is likely that these spots

Fig. 7. (Color online) \( Y \) maps of Dot 2 measured with the NUV laser at \( V_{\text{bias}} = 0, -9, -18, -27, -36, -45 \) V.

Fig. 8. (Color online) Optical microscope images of Dot 2 (a) before and (b) after the SIPM measurements as shown in Fig. 7.
Fig. 9. (Color online) Y maps of Dot 2 measured with the green laser at $V_{bias} = 0$ V (a) before and (b) after the SIPM measurements as shown in Fig. 7, and (c) calculated $q/\phi_B$ map.
were formed by the voltage stress. We succeeded in in situ monitoring of the initial stage of the degradation.

Figure 8 shows the optical microscopy images of Dot 2 (a) before and (b) after the SIPM measurements. The same spotted pattern as the $Y$ map at $V_{bias} = −45 \text{ V}$ in Fig. 7 is observed in the image after the measurements. In the spots, the electrode surface became rough. As well as in the $Y$ maps with the green laser at $V_{bias} = 0 \text{ V}$ (a) before and (b) after the SIPM measurements as shown in Figs. 9(a) and 9(b), the same results were obtained. Unfortunately, the $q\phi_B$ value was not determined in the spots as shown in Fig. 9(c), because the photocurrent was so small and unstable. Figure 10 shows the $I$–$V$ characteristics before and after the SIPM measurements. In the forward $I$–$V$ characteristics, slight increase of the current is observed up to $+0.8 \text{ V}$, which indicates slight decrease of $q\phi_B$. In the reverse characteristics, the current level is the same down to $−4 \text{ V}$, but the leakage current increased to $200 \text{ pA}$ at $−50 \text{ V}$. We can speculate that the degraded region is not uniform and consists of two interfaces. One interface is reacted by the voltage application, which is not flat and shows weakly characteristics especially under a large reverse bias voltage. The other one is the burned-out interface by more intensive interfacial reaction, which induces a loss of the active area of the electrode. These two regions are microscopically mixed in the degraded region under the spatial resolution of SIPM. As for the SIPM result with the green laser without a bias voltage, as the area loss is dominant, the signal was small in the degraded region. On the other hand, with the NUV laser, as the carrier generation was enhanced by induced defects upon the interfacial reaction in the vicinity of the interface, a large signal was obtained. Therefore, we demonstrated that SIPM clearly visualized an initial stage of the degradation sensitively in conjunction with the electrical characteristics.

One possible model of the degraded mechanism might be existence of bunches of dislocations. We used the VAS technology for the substrate growth, but the distribution of the dislocation is not completely uniform. The large $Y$ regions may include bunches of dislocations, which can induce large-structure defects. For further study, cathode luminescence and X-ray topography measurements of the GaN surfaces are required to clarify the origin of such regions.

4. Conclusions

SIPM was applied to characterize the initial stage of the degradation of Ni/n-GaN Schottky contacts formed on a thick n-GaN layer grown on a freestanding GaN substrate by applying $V_{bias}$ down to $−45 \text{ V}$. Most of the contacts showed small reverse biased current below the noise floor at $−50 \text{ V}$, and uniform distribution was observed in the $Y$ maps over the electrode with the visible lasers. Irregular-shape regions with 5%–25% larger $Y$ appeared with the NUV laser by applying $V_{bias}$, but the $I$–$V$ characteristics were stable.

On the other hand, for the contacts with a slightly larger reverse current of around $10^{-9}$ order at $−50 \text{ V}$, the $Y$ maps were also uniform at $V_{bias} = 0 \text{ V}$, but over $V_{bias} = −36 \text{ V}$, two spots appeared within the large $Y$ regions at $V_{bias} = −36 \text{ V}$. After the SIPM measurements, the $I$–$V$ characteristics became leaky, and the same spots were observed in the microscope image of the electrode. We demonstrated that SIPM clearly visualized an initial stage of the degradation as an in situ monitoring in conjunction with the electrical characteristics.

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