Defect Formation in GaN introduced during Plasma Processing

S. Nakamura, M. Suda, M. Suhara, and T. Okumura

Division of Electrical and Electronic Engineering, School of Science and Engineering, Tokyo Metropolitan University
1-1 Minami Ohsawa, Hachioji, Tokyo, 192-0397 Japan
E-mail: nakamura@eei.metro-u.ac.jp

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Abstract

We have studied the electrical characteristics of n-GaN exposed to plasma. In the case of hydrogen plasma, the decrease in leakage current as well as carrier density was clearly observed in the planer-type n-GaN Schottky diodes. In addition the decrease in carriers was also observed in the n-GaN layer exposed to argon plasma, while the increase in leakage current was observed. Thus, these results indicate that hydrogen atoms passivate the defects in the subsurface region. On the other hand, any notable change in electrical properties was not observed in the case of nitrogen plasma treatment. Therefore, it is considered that the decrease in carrier density was related to the intrinsic defects associated with the deficiency of nitrogen atoms.

INTRODUCTION

Gallium nitride (GaN) is a promising material for high-power, high-frequency and high-temperature operating devices. For the device fabrication, dry etching techniques have been used because of chemical stability of GaN. These devices fabricated by means of the plasma processing have many problems, such as plasma induced damages and hydrogen passivation. Hydrogen as a common contaminant incorporates during growth and processing, and affects the electrical properties of semiconductors. For GaN, it is well studied that the Mg acceptor in p-GaN is passivated by forming the Mg-H complexes [1-4]. On the other hand, the behavior of hydrogen in n-GaN has not been well understood to date, particularly in relation to the electrical properties. In reports [5, 6], the hydrogen incorporation is thought to be responsible for the current instability (collapse) in GaN-based field effect transistors and the inhomogeneity of carrier profiles in undoped GaN. Therefore, it is important to investigate the effect of hydrogen incorporation on the electrical properties.

In general, the hydrogen plasma treatment has been performed for the studies on the hydrogen passivation effects in semiconductors. However, it is well known that the plasma exposure might introduce the damages related to the degradation of the electrical properties. Furthermore, the plasma-induced damages in GaN are not clarified at present.

In this paper, we compare the electrical characteristics of the Schottky diodes fabricated on Si-doped *n*-GaN exposed to three different gaseous plasmas, and discuss the role of hydrogen atom and plasma-induced damages.

EXPERIMENTAL PROCEDURES

Si-doped *n*-GaN layers used in this work were grown on (0001) sapphire substrates by metalorganic chemical vapor deposition and its carrier density was 2 x 10^{17} cm^{-3}. In order to characterize electrical properties for the GaN layers exposed to plasmas (H_2, Ar, and N_2), planer-type Schottky diodes were fabricated. Ni and Ti/Al were used as the Schottky and ohmic contacts, respectively. Ti/Al (25nm/100nm) ohmic-contact metal layers were deposited by using both EB- and resistive-heating evaporators, followed by the rapid thermal annealing in the N_2 ambient at 725 ^{o}C for 200 seconds. Prior to the deposition of the Ni Schottky contact, the GaN surface was exposed to plasma for 60 min by using a remote RF (13.56 MHz, 80 W) plasma system. The chamber was evacuated below 10^{-6} Torr prior to introducing gas at a pressure of 0.6 Torr. The distance between the glow-discharge plasma region and the substrate surface was 15 cm. The Ni Schottky electrode was formed on the plasma-exposed surfaces. Current-voltage (*I-V*) and capacitance-voltage (*C-V*) characteristics were measured in order to evaluate the subsurface damage and shallow-donor profiles, respectively. Photocapacitance measurements were also performed.

RESULTS AND DISCUSSIONS

Figure 1 shows both forward and reverse current-voltage (*I-V*) characteristics of Ni/*n*-GaN Schottky diodes exposed to H_2 (open circles) and Ar (dashed line) plasmas. As a reference, the *I-V* curve taken from the *n*-GaN Schottky diode without any plasma treatment (untreated) is also shown in Fig. 1(solid line). Both untreated and H_2 plasma treated samples show the nearly ideal *I-V* characteristics with an *n*-value of 1.06 and 1.07, respectively. It is clearly shown that the leakage current for the H_2-plasma treated sample is suppressed by 1-2 orders of magnitudes compared to that for the untreated sample. In addition, the apparent SBH for the H_2-plasma treated sample is increased

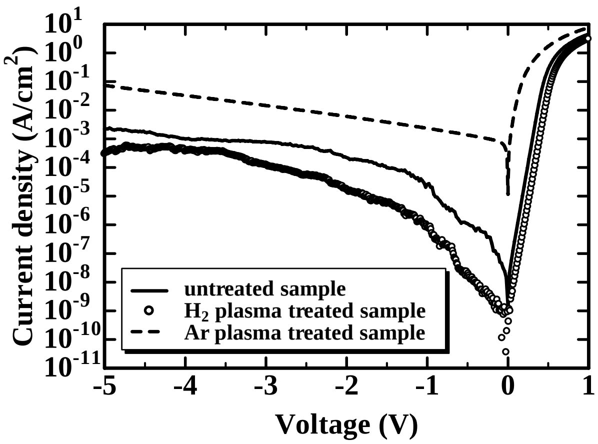

Fig.1. *I-V* characteristics of Ni/*n*-GaN Schottky diodes with and without plasma treatment.

compared to that for untreated samples. On the other hand, the Ar plasma treated samples show poor *I-V* characteristics with a high value of *n*, low value of SBH. It is noted that anomalously high (apparent) value of SBH is obtained by means of the *C-V* measurement compared with the other samples. From these results, in the case of hydrogen plasma treatment, it is considered that the positively-charged defects and/or ionized Si donors, in the very vicinity of the top surface are passivated by atomic hydrogen. On the contrary, it is found that the Ar plasma treatment introduces a large number of defects at the top-surface region. The observed degradation of the *I-V* characteristics for the Ar-plasma treated samples is thought to be caused by the ion-impact damage because larger mass of Ar ion compared to that for hydrogen ion.

Figure 2 shows the depth profiles of carrier density for the Ni/*n*-GaN Schottky diodes with and without plasma treatment for 60 min. In the case of the untreated sample, the carrier profile is uniform through the measuring range. On the other hand, for the H_2 and Ar plasma treated samples, the carrier density decreases down to the depth of 0.15-0.2 μm from the top surface. This decrease in carrier density associated with hydrogen plasma treatment for the other semiconductors is well known as a hydrogen passivation [7-9]. Then, this decrease in carrier density can be thought to be due to the deactivation of donors by hydrogen. However, similar results are also observed for the Ar-plasma treated samples. In addition, the magnitude of the carrier-density decrease for the Ar-plasma treated sample is larger than that for the H_2-plasma treated sample. Consequently, this difference in the magnitude of the carrier-density decrease is thought to be due to the larger mass of Ar ion compared to that of hydrogen ion. On the other hand, the projection range of the Ar ion is estimated to be less than several nm. Therefore, the decrease in the carrier density is thought to be due to the deactivation or compensation by some intrinsic defects, which are introduced on the top surface upon ion-impact and diffuse into the sub-surface region. In the case of nitrogen plasma treatment, any notable decrease in carrier density was not observed. Therefore, it is considered that the decrease in the carrier density was related to the compensation or passivation by the intrinsic defects due to the deficiency of nitrogen.

Figure 3 shows the photocapacitance spectra taken from the Ni/*n*-GaN Schottky diodes with and without plasma treatment for 60 min. The PHCAP signal increases with increasing the energy of the illuminated photon energy above 1.5 to 2.5 eV for untreated, H_2 and Ar plasma treated samples. On the other hand, the notable PHCAP signal was not observed for the N_2 plasma treated sample. It is found that these energy levels correspond to the yellow luminescence (YL) band. This result indicates that the H_2 and Ar plasma treatments introduce the defects related to the YL. It is reported that the origin of YL is an isolated Ga vacancy (V_{Ga}) or a complex between a V_{Ga} and a donor impurities [10-13]. In addition, it is reported that the formation energy of V_{Ga} under the Ga rich condition is lower than that of other defects [14]. Therefore, it is considered

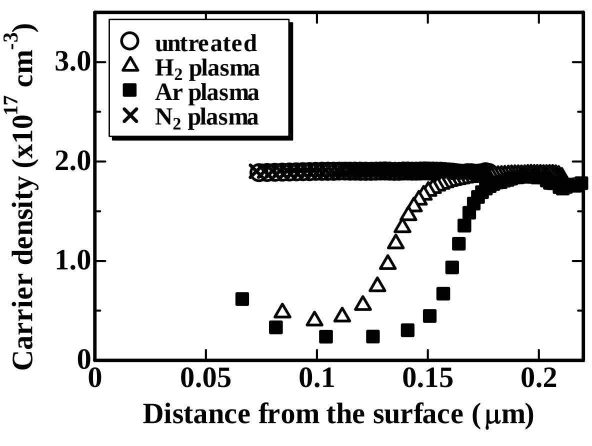

Fig. 2. Depth profiles of the carrier density for the Ni/*n*-GaN Schottky diodes with and without plasma treatment.

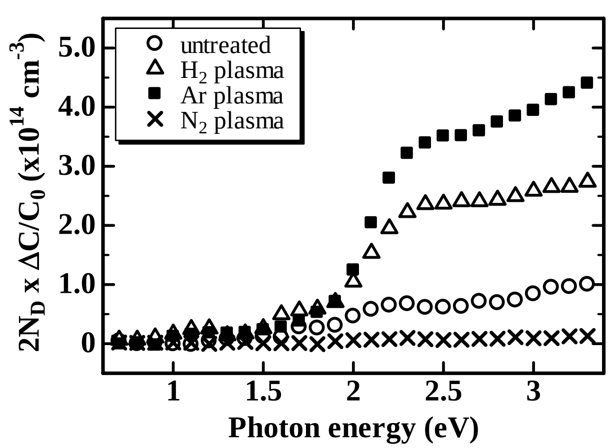

Fig. 3. photocapacitance spectra taken from the Ni/*n*-GaN Schottky diodes with and without plasma treatment for 60 min.

that the GaN surface exposed to H_2 or Ar plasma is in nitrogen deficiency condition, i.e., Ga rich condition, thus there is a large amount of V_{Ga} in the vicinity of the GaN surface. On the contrary, in the case of the N_2 plasma treatment, GaN surface is in N rich condition, then it is difficult to generate the V_{Ga} and surface defects such as nitrogen vacancy become ineffective. On the other hand, as the origin of the defects associated with the decrease in carrier, it can be thought to be the other defects (interstitial gallium, gallium antisite, nitrogen vacancy, and their complexes) because there are a large number of the excess Ga atoms and nitrogen vacancies under the Ga rich conditions. However, the detail mechanism of carrier decrease is not clarified at the present stage. Therefore, it is important to study the possibility of the reactivation of carriers or the recovery of the plasma induced damages for the sample exposed to H_2 or Ar plasma.

CONCLUSIONS

We have investigated the electrical properties of the Schottky diodes fabricated on Si-doped *n*-GaN exposed to three different gaseous plasmas. Our new findings are:

1. Hydrogen atoms passivate native defects in the very vicinity of the GaN surface. We observed that the H_2-plasma exposure clearly improved the I-V characteristics for the Schottky diodes.
2. Both H_2- and Ar-plasma treatments reduce the carrier density in the subsurface region of n-GaN. The observed carrier-density profiles are very similar to each other.
3. Any notable change in electrical properties was not observed in the case of nitrogen plasma treatment.
4. The carrier-density decrease in the plasma treated n-GaN layers might be related to the intrinsic defects associated with the deficiency of nitrogen.

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