Bias Annealing Behavior of Plasma-Induced Defects in n-GaN Exposed to Plasma

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

Keywords: reverse bias annealing, plasma-induced defects, reactivation, deactivation, gallium nitride

Abstract

The behavior of plasma-induced defects deactivating Si donors in GaN has been studied by using Schottky diodes with and without an applied bias voltage. We found the Si donors are deactivated down to 100-200 nm from the surface upon plasma irradiation at room temperature for 30-60 min. It is interesting that annealing of deactivated GaN with a reverse bias applied to a Schottky diodes leads to an enhancement of "reactivation" of the donor at temperatures much lower than 200 ^{o}C. It is speculated that the plasma-induced defects are responsible for the deactivator of the doped Si donors in GaN.

INTRODUCTION

Dry plasma etching is almost exclusively used to form the device structures, e.g., "mesa" structure, for GaN based devices because of chemical stability of GaN. The plasma processing has many problems, such as plasma induced damages and hydrogen passivation. It is well known that the plasma exposure might introduce the damages related to the degradation of the electrical properties. However, the plasma-induced damages in GaN are not well clarified at present. Therefore, it is important to understand the electrical properties for the plasma-treated GaN layers.

Recently, we have investigated that 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. In addition, any notable change in electrical properties was not observed in the case of nitrogen plasma treatment. Therefore, the carrier-density decrease in the plasma treated n-GaN layers might be related to the intrinsic defects associated with the deficiency of nitrogen atoms. However, the origin of the observed plasma-induced damages is not clarified.

In the case of GaAs exposed to hydrogen plasma, it is well known that the hydrogen atoms passivate the donors in the n-type GaAs as well as the acceptors in p-type GaAs [1-7]. In order to study the incorporation as well as passivation mechanism, the dissociation of the hydrogen-donor complexes was demonstrated by several authors [8-12]. In addition, the dissociation energy was also discussed for obtaining the knowledge to study the configuration of the hydrogen-defect complexes. Therefore, it is important to understand the dissociation process of donor-defect complexes in plasma-treated GaN in order to clarify the mechanism of the carrier decrease in the n-GaN exposed to H_2 or Ar plasma.

In this paper, we present the electrical properties of the Schottky diodes fabricated on Si-doped *n*-GaN exposed to H_2 plasma. Particularly, In order to clarify the mechanism of the carrier deactivation, a series of isothermal annealing (423 K) processes, namely the reverse bias annealing (RBA), was carried out by applying various bias voltages to the Ni/*n*-GaN Schottky diodes.

EXPERIMENTAL PROCEDURES

The Si-doped *n*-type GaN layers used in this work were grown on (0001) sapphire substrates by metalorganic chemical vapor deposition. The layer thickness and net donor concentration of Si-doped GaN epitaxial layers were approximately 2 μm and $2x10^{17}$ cm^{-3}, respectively. In order to characterize electrical properties for the GaN layers exposed to H_2 or Ar plasma, planer-type Schottky diodes were fabricated. Ti/Al (25nm/100nm) ohmic-contact metal layers were deposited by using both electron beam 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 30 or 60 min by using a remote RF (13.56 MHz, 80 W) plasma system. The Ni Schottky electrode was formed on the plasma-exposed surfaces. Capacitance-voltage (*C-V*) characteristics were measured in order to evaluate the subsurface damage and shallow-donor profiles, respectively. Furthermore, a series of isothermal annealing processes in the air atmosphere was carried out by applying various bias voltages to the Schottky diodes. A typical bias annealing temperature was 150^{o}C.

RESULTS AND DISCUSSIONS

Figure 1 shows the carrier profiles for the Ni/*n*-GaN Schottky diodes with and without plasma treatment for 60 min. The carrier profile of the untreated sample is uniform through the measuring range. On the other hand, for the H_2 and Ar plasma treated samples, the carrier density decreases

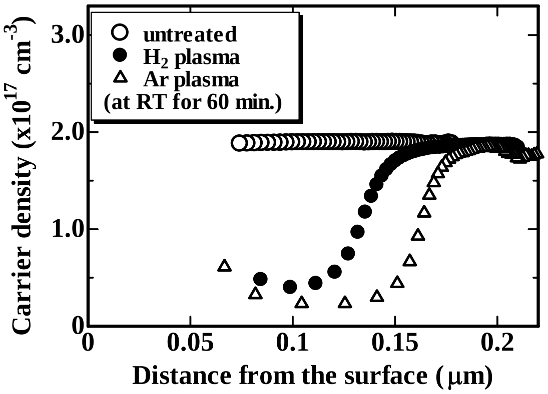

Fig. 1. Depth profiles of the carrier density for Si-doped GaN with and without plasma treatment.

down to the depth of 0.15-0.2 μm from the top surface. This result indicates that the Si donors were passivated by the plasma-induced defects because the similar results were observed for both H_2- and Ar-plasma treated samples. 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 by some intrinsic defects, which are introduced on the top surface upon ion-impact and diffuse into the sub-surface region. It is considered that a candidate for origin of the carrier decrease is the Si-defects complexes. Therefore, in order to clarify the mechanism of the carrier decrease in the n-GaN exposed to H_2 or Ar plasma, the reverse bias annealing (RBA) were performed.

Figure 2 shows the depth profiles of the carrier concentration for the 30-min-H_2 plasma treated Ni/*n*-GaN Schottky diodes after the RBA at 2 and 5 V for 30 min. As a reference, the depth profiles of the carrier concentration for the Ni/*n*-GaN Schottky diodes with H_2 plasma treatment after the isothermal annealing without applying voltage is also shown in Fig. 2. In the case of the annealing at 150°C without applying voltage, any notable change of the depth profile was not observed. Similarly, in the case of low temperature annealing, such as room temperature, with applying voltage, the any notable change was not observed (not shown here). On the other hand, the depth profile near the surface region increased after the RBA at 2 V. In addition, in the case of the RBA at 5 V, the depth profile was recovered at the initial level before exposing the H_2 plasma. These results indicate that the defects related to this behavior, i.e., carrier activation, might be caused by the positively charged defects in this sub-μm region, because the negative bias is attributed to the recovery of the carrier deactivation. Therefore, it is considered that the reverse bias as well as temperature plays important roles of this carrier reactivation. In order to clarify the effects of bias voltage and annealing temperature on the carrier reactivation, further examination was performed as below.

Figure 3 shows the time variation of the carrier depth profiles for the 60-min-H_2 plasma treated Ni/*n*-GaN Schottky diodes with RBA at 2 V. The annealing temperature was fixed at 150°C, and *C-V* measurements were performed at room temperature. With increasing the annealing time, the carrier concentration in the vicinity of the top surface region increased. In addition, the carrier concentration at the near-surface region was almost recovered its initial value by further annealing. On the contrary, the carrier concentration in deeper region from the depletion region at the reverse bias of 2 V is almost unchanged. As a result, the depth profile of carriers for RBA at 2 V results in the "V" shaped profile. However, for the RBA at 3 V as shown in Fig. 2, the final profile is almost flat. These results indicate that the reverse bias is related to the range of recovery region. Therefore, it is considered that

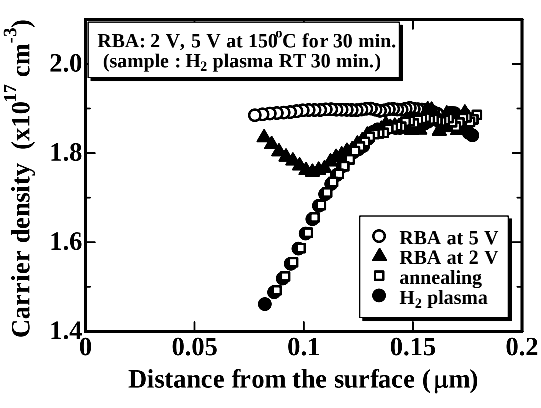

Fig.2. Depth profiles of the carrier concentration for the H_2 plasma treated Ni/*n*-GaN Schottky diodes after the RBA at 2 and 5 V.

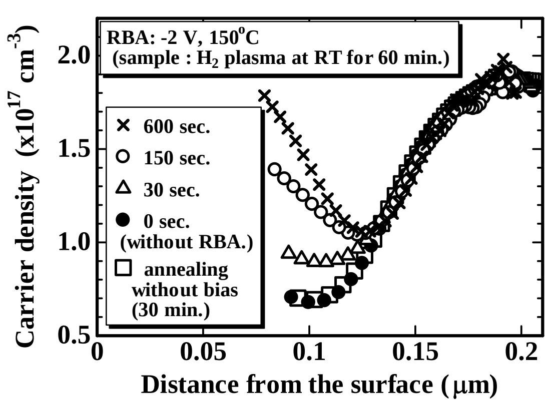

Fig. 3. Time variation of the carrier depth profiles for the H_2 plasma treated Ni/*n*-GaN Schottky diodes with RBA at 2 V.

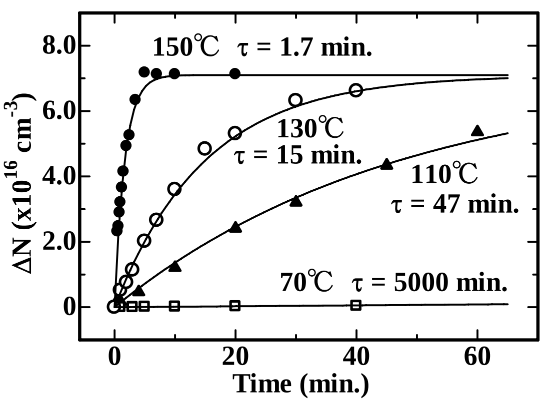

Fig. 4. Time variation of the recovered carrier concentration at the 100 nm depth from the surface for the H_2 plasma treated Ni/*n*-GaN Schottky diodes with RBA at 2 V at the different temperatures.

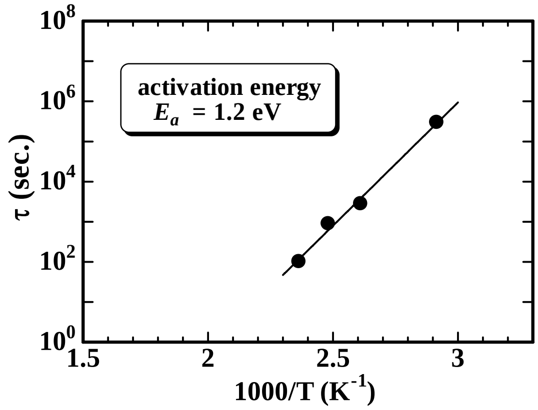

Fig. 5. Arrhenius analysis of the 2-V-RBA dissociation time for the Si-defects complexes in the H_2 plasma treated Ni/*n*-GaN Schottky diodes

the bottom of the valley is related to the so-called λ point, where the quasi-Fermi level intersects the deep level, associated with the plasma-induced defects (named as “D”). When the Schottky diode is applied the reverse bias voltage, the D located above the quasi-Fermi level increase. It is considered that these deep levels, such as D-Si complexes, above the quasi-Fermi level can easily dissociate to D and Si by thermal annealing. Furthermore, the dissociated D is removed from the depletion region by the electric field under the reverse bias. Therefore, the charge state of D might be positive. On the other hand, that of D formed the D-Si complex should be negative, because the charge state of ionized Si donor is positive at room temperature. These results indicate that the D might be the negative-U type defects.

Figure 4 shows the time variation of the recovered carrier concentration at the 100 nm depth from the surface for the H_2 plasma treated Ni/*n*-GaN Schottky diodes with RBA at 2 V at the different temperatures. With increasing the annealing temperature, the recovery rate becomes high. On the other hand, the recovered carrier concentrations saturate at the same value. This saturation means full recovery of the initial carrier concentration before H_2 plasma exposure. Therefore, it is considered that the annealing temperature accelerates the dissociation of the defects complexes located above the quasi-Fermi level. It is interesting that annealing of deactivated GaN with a reverse bias applied to a Schottky diodes leads to an enhancement of "reactivation" of the donor at much lower temperatures than 200 ^{o}C. Arrhenius analysis of the dissociation time is shown in Fig. 5 and yields the activation energy Ea for the dissociation RBA process from the relation

$$\tau = \tau_0 \, exp\left[E_a / \left(k_B T\right)\right] \, , \qquad (1)$$

where k_B is Boltzmann’s constant and T is the absolute temperature during a RBA. The straight solid line in Fig. 5 is the least-squares fit of Eq. (1) to the dissociation time. From the fitting result, the dissociation energy E_a and prefactor τ_0 were estimated to be approximately 1.2 eV and 3.5 x 10^{-13} sec, respectively. The thermal activation energy essentially equals the binding energy of the constituents of the complex. However, In the case of RBA, electric field also assists the dissociation of the complexes. Therefore, the bias dependence of the activation energy might be required for precise discussion for the dissociation mechanism of complexes.

CONCLUSIONS

We have investigated the reverse bias annealing for the H_2 plasma treated Ni/*n*-GaN Schottky diodes. Our new findings are:

1. Annealing of deactivated GaN with a reverse bias applied to a Schottky diodes leads to an enhancement of "reactivation" of the deactivated donor at much lower temperatures than 200 ^{o}C.
2. The magnitude of the reverse bias is related to the range of the carrier recovery region.
3. The the dissociation of the plasma-induced defect-Si complexes located above the quasi-Fermi level is thermally activated under the RBA condition.
4. The plasma-induced defects might be the negative-U type defects.

REFERENCES

[1] J. Chevallier, W. C. Dautremont-Smith, C. W. Tu, and S. J. Pearton, Appl. Phys. Lett. **47**, 108 (1985).

[2] J. Weber, S. J. Pearton, and W. C. Dautremont-Smith, Appl. Phys. Lett. **49**, 1181 (1986).

[3] S. J. Pearton, W. C. Dautremont-Smith, J. Chevallier, C. W. Tu, and K. D. Cummings, J. Appl. Phys. **59**, 2821 (1986).

[4]N. M. Johnson, R. D. Burnham, R. A. Street, and R. L. Thornton, Phys. Rev. B **33**, 1102 (1986).

[5] S. J. Pearton, J. W. Corbett, and T. S. Shi, Appl. Phys. A **43**, 153 (1987).

[6] N. Pan, S. S. Bose, M. H. Kim, G. E. Stillman, F. Chambers, G. Devance, C. R. Ito, and M. Feng, Appl. Phys. Lett. **51**, 596 (1987).

[7] A. Paccagnella, A. Callegari, E. Latta, and H. Gasser, Appl. Phys. Lett. **55**, 259 (1989).

[8] H. Y. Cho, E. K. Kim, S-K. Min, K. J. Chang, and C. Lee, J. Appl. Phys. **68**, 5077 (1990).

[9] R. A. Morrow, J. Appl. Phys. **74**, 6174 (1993).

[10] G. Roos, N. M. Johnson, C. Herring, and J. S. Harris, Appl. Phys. Lett. 59, 461 (1991).

[11] S. J. Pearton, C. R. Abernathy, and J. Lopata, Appl. Phys. Lett. 59, 3571 (1991).

[12] A. W. R. Leitch, Th. Prescha, and J. Weber, Phys. Rev. B 44, 5912 (1991).