Microstructures Observation of N-type GaN Contacts and the Electrical Properties†

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Abstract

In the present study, to increase the carrier density of n-GaN, the formation of N-vacancies are attempted by interfacial reaction and by Ar ion irradiation. The microstructure and electrical properties after the interfacial reaction and Ar ion irradiation were then analyzed by TEM and DC conduction tests. The TEM result indicates that Ti_2N is formed adjacent to the GaN substrate after the deposition of Ti film. The Ti_2N formation indicated that a huge amount of N-vacancies is formed within the subsurface of GaN. The electrical conduction profile reveals that even with the formation of Ti_2N, ohmic conduction is achieved. It is likely due to the formation of N-vacancies by interfacial reaction to form Ti_2N and Ar ion irradiation. By prolonging the Ar ion irradiation, further improvement of electrical conductivity is achieved. This result indicated that the amount of N-vacancies formation within the GaN subsurface are depending to the Ar ion irradiation times. However, by performing Ar ion irradiation for 3600 s, no further improvement is achieve. It is likely due to phase transformation from GaN to Ga-rich phase at the GaN subsurface. The Ga-rich phase enhance the Ga-Ti compound, which increase the height and width of the Schottky barrier, thus reduce the electrical conductivity.

KEY WORDS: (N-type gallium nitride), (Ohmic contacts), (Schottky barrier), (N-vacancies), (Microstructures), (Electrical properties)

1. Introduction

Due to the physical limitation of silicon, which is still used in most of today's power electronic devices, it is important to seek for better alternative materials for use in the next-generation power electronic devices. Gallium nitride (GaN) is one of the most promising candidates. Compared with silicon, GaN-based power electronic devices promising higher energy efficiency devices, with capability of handling higher power and longer service life [1, 2]. However, in spite of having a significant development in the growth [3, 4] and processing technology of light emitting diodes (LED) and laser diodes (LDs) [5], the application of GaN semiconductor as power electronic devices is still far from real.

One of the main problems is to form low-resistance ohmic contact between GaN and metallic outer circuits [6]. Without the formation of adequate ohmic contact, the interference of carriers (Schottky barrier) will occur at the contact interface, which generates Joule heat and deteriorates the energy efficiency and the reliability of the devices. To form ohmic contact, this barrier need to be lowed and/or thinned.

To reduce the Schottky barrier height, contact materials with adequate value of work function is needed. In the case of n-type GaN, a contact material with work function value lower than electron affinity of GaN (4.11 eV) is required.

To thinning the Schottky barrier, it is effective to increase the carrier density of the GaN. The conventional method to increase the carrier density is by increasing the implanted dopant density. The other method to increase the carrier density in n-GaN is by increasing the N-vacancies within the GaN subsurface. These vacancies are known to act as n-type dopant atoms with a donor level very close to the conduction band edge of n-type GaN [7]. The N-vacancies can be formed by many methods. In the present study, the formation of N-vacancies within the GaN subsurface are attempted by interfacial reaction and by Ar ion irradiation.

During the sputter-deposition process of Ti films, interfacial reaction between deposited Ti films and GaN were expected to occur. The reaction between Ti and GaN at low temperature form several intermetallic compound such as TiN and Ti_2N as shown in **Figure 1**. By the formation of TiN and/or Ti_2N which consuming N atoms from GaN, the N-vacancies within the subsurface of GaN will be formed. However, to form ohmic contact with n-type GaN, TiN are more preferred. This is due to the lower work function of TiN (3.74 eV) [8] compared to Ti_2N.

The other method attempted to form N-vacancies within the GaN subsurface are Ar ion bombardment during the sputter-cleaning of the GaN surface before the sputter-deposition process. Sputter-cleaning is a conventional method to remove oxide layer from the sputter target and the substrates surfaces by

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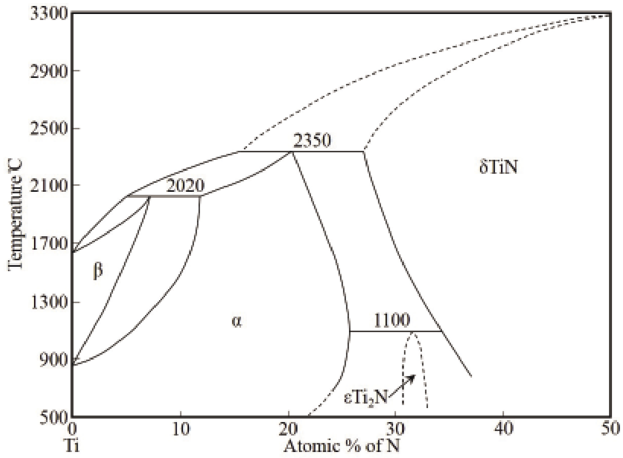

Fig. 1 Phase diagram of Ti-N [9].

using Ar ion bombardment. By prolonging the sputter-cleaning times of the GaN surface, it is expected that severe radiation damage is induced in the subsurface of the GaN and vacancies is formed. It have been reported that by sputtering the GaN surfaces under a threshold energy, N atoms were mostly sputtered [10]. By sputtering with higher energy, the Ga atoms were also sputtered. However, Ga atoms were always sputtered with N atoms in pairs. Therefore, by performing a prolonged the sputter-cleaning of the GaN surface with a low sputtering energy, N atoms will be sputtered from GaN, thus leading to the formation of N-vacancies.

In the present study, to increase the carrier density of n-GaN, the formation of N-vacancies are attempted by interfacial reaction and by Ar ion irradiation. The microstructure and electrical properties after the interfacial reaction and Ar ion irradiation were then analyzed by transmission electron microscopy (TEM) and direct current (DC) conduction tests.

2. Experimental procedure

Substrates used in the present study were 350-µm-thick, (0001) single crystal n-GaN and 6.5-µm-thick, (0001) single crystal undoped-GaN layer epitaxially grown on a (0001) sapphire layer. The sizes of all substrates were 4.0-mm-square. The electron mobility and carrier density of the n-GaN substrates were 1.6×10^6 m^2/Vs and 5.1×10^{24} cm^{-3}, respectively. Before the deposition process, the substrates were cleaned with acetone applying ultrasonic vibration. Then the substrates were fixed in a radio-frequency magnetron sputtering deposition apparatus using 1.0-mm-wide Al masking ribbons. Before the sputter deposition, the surfaces of Ti target and the substrates were sputter-cleaned for 300 s to remove native oxide layer. For some n-GaN substrates, the sputter-cleaning times were prolonged to 600, 1200, 2400 and 3600 s to induce the formation of N-vacancies. In present study, the sputter-cleaning times are to be referred to as (300~3600 s Ar). Both of sputter-cleaning and sputter-deposition were performed in 8.0 Pa of 99.9999% Ar under the RF power of 200 W. The sputter deposition of Ti films on the substrates was performed immediately after the sputter-cleaning.

The microstructure and electrical properties of the specimens were then analyzed by TEM and DC conduction tests at 273 K.

3. Results and discussion

Figure 2 shows the microstructure of the n-GaN/Ti (300 s Ar) specimen after the Ti deposition. In the bright-field image shown in **Figure 2 (a)**, a layer of approximately 12-nm-thickness is observed adjacent to GaN substrate. **Figure 2 (b)** shows the electron diffraction pattern taken from this area. The diffraction pattern consists of net patterns of GaN and Ti_2N. **Figure 2 (c)** shows the dark-field image of the same area taken by using the Ti_2N 020 diffraction as mark in **Figure 2 (b)**. The image shows that only the layer adjacent to GaN substrate appear bright. Thus, it is concluded that a layer of Ti_2N is formed adjacent to GaN substrate by the Ti deposition on the GaN substrate. The N constituting Ti_2N formation are originated only from the GaN substrate. So it is likely that a huge amount of N-vacancies is formed within the GaN subsurface near to the contact interface.

Figure 3 shows the electrical conduction profile of the specimens. The electrical conduction profile of n-GaN/Ti (300 s Ar) indicates that ohmic contacts are formed by the formation Ti_2N during the Ti deposition and/or by Ar ion irradiation during sputter-cleaning. Theoretically, Ti_2N is not an adequate materials for ohmic formation of n-GaN due to its high work function. However, the results indicates that even with a Schottky barrier formed at the interface, the formation of Ti_2N and/or Ar ion irradiation has induced a sufficient amount of N-vacancies within the GaN subsurface to make the barrier thin enough to achieve ohmic conduction. The electrical conduction of undoped-GaN/Ti (300 s Ar) contact shown in **Figure 3** also comply with this result.

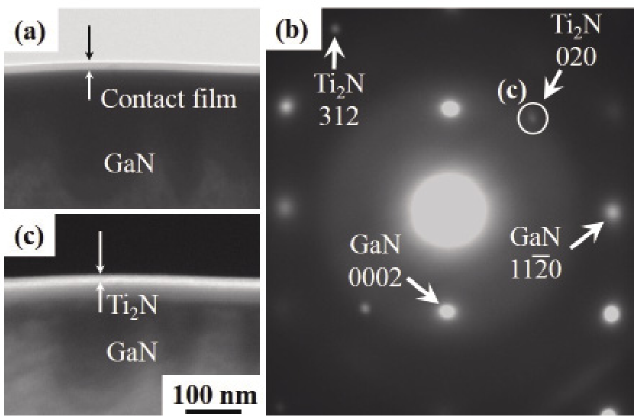

Fig. 2 Microstructure of the n-GaN/Ti (300 s Ar) contact without annealing. (a) bright-field image, (b) selected area electron diffraction pattern of the area shown in (a), (c) dark-field image of the area shown in (a) using Ti_2N 020 diffraction [11].

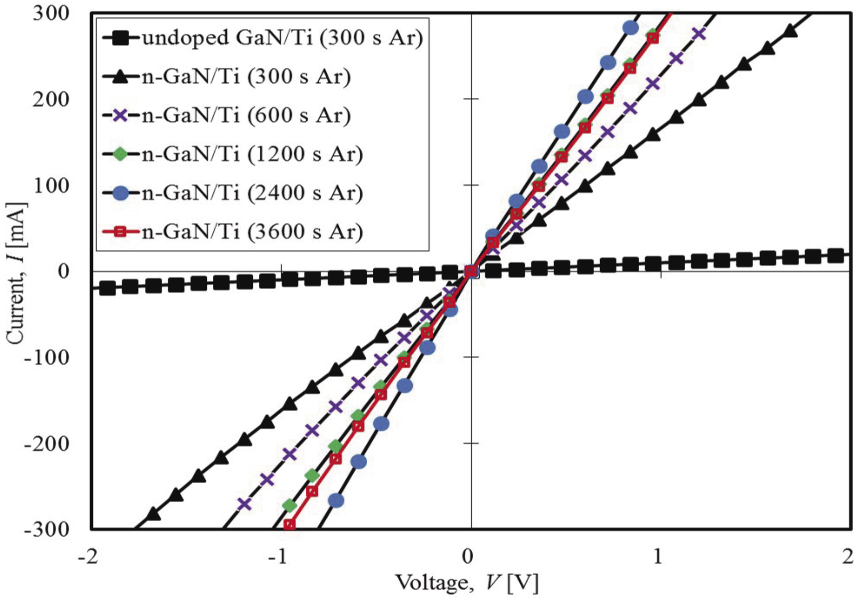

Fig. 3 Electrical conduction profile of the specimens [12].

Even with a very low initial carrier density, due to no dopant implantation, the Ti_2N formation and/or Ar ion irradiation induced sufficient amount of N-vacancies and carrier density to achieve ohmic conduction. The low electrical conductivity of undoped-GaN/Ti contact is attributed to the high specific resistance of undoped GaN substrate.

The effect of N-vacancies formation by prolonging the Ar ion irradiation times to 600, 1200, 2400 and 3600 s can be seen in the electrical conduction profile of n-GaN/Ti contacts as shown in **Figure 3**. All the electrical conduction profile except for specimen subjected to 3600 s Ar ion irradiation time indicates that ohmic conduction have been achieved. Additionally, the electrical conduction profile shows that longer Ar ion irradiation time resulting to higher electrical conductivity. This result indicated that the amount of N-vacancies formation within the GaN subsurface are depending to the Ar ion irradiation time. However, the electrical conduction profile of specimen with 3600 s Ar ion irradiation show no further improvement compared to specimen with 2400 s Ar ion irradiation time. This is likely due to the selective sputtering of N atoms from GaN substrate. This selective sputtering has induced the phase transformation from GaN to Ga-rich at the GaN subsurface. The Ga-rich phase has enhance the formation of Ga-Ti compound at the interface during the Ti deposition. The formation of Ga-Ti compound will increase the height and width of the Schottky barrier. The formation of Ga-Ti compound also will reduce the number of N-vacancies within the subsurface of GaN, thus further increase the width of the Schottky barrier and reduce the electrical conductivity.

4. Conclusions

To increase the carrier density of n-GaN, the formation of N-vacancies are attempted by interfacial reaction and by Ar ion irradiation. The microstructure and electrical properties after the interfacial reaction and Ar ion irradiation were then analyzed by TEM and DC conduction tests. The TEM result indicates that Ti_2N is formed adjacent to the GaN substrate after the deposition of Ti film. The Ti_2N formation indicated that a huge amount of N-vacancies is formed within the subsurface of GaN. The electrical conduction profile reveals that even with the formation of Ti_2N, ohmic conduction is achieved. It is likely due to the formation of N-vacancies by interfacial reaction to form Ti_2N and Ar ion irradiation. By prolonging the Ar ion irradiation, further improvement of electrical conductivity is achieved. However, by performing Ar ion irradiation for 3600 s, no further improvement is achieve. It is likely due to phase transformation from GaN to Ga-rich phase at the GaN subsurface. The Ga-rich phase enhance the Ga-Ti compound, which increase the height and width of the Schottky barrier, thus reduce the electrical conductivity.

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References

1) M. Asif Khan, Q. Chen, M. S. Shur, B. T. Dermott, J. A. Higgins,J. Burm, W. J. Schaff and L. F. Eastman, "GaN based heterostructure for high power devices", Sol. Stat. Electron., 41 (1997), 1555-1559.

2) A.P. Zhang, F. Ren, T. J. Anderson, C. R. Abernathy, R. K. Singh, P. H. Holloway, S. J. Pearton, D. Palmer and G. E. McGuire, "High-Power GaN Electronic Devices", Critic. Rev. Solid. Stat. Mater. Sci., 27 (2002), 1-71.

3) K. Motoki, T. Okahisa, S Nakahata, N. Matsumoto, H. Kimura, H. Kasai, K. Takemoto, K. Uematsu, M. Ueno, Y. Kumagai, A. Koukitu and H Seki, "Growth and characterization of freestanding GaN substrates", J. Cryst. Growth, 237-239 (2002), 912-921.

4) Y. Mori, M. Imade, K. Murakami, H. Takazawa, H. Imabayashi, Y. Todoroki, K. Kitamoto, M. Maruyama, M. Yoshimura, Y. Kitaoka and T. Sasaki, "Growth of bulk GaN crystal by Na flux method under various conditions", J. Cryst. Growth, 350 (2012), 72-74.

5) I. Akasaki, "Key inventions in the history of nitride-based blue LED and LD", J. Cryst. Growth, 300 (2007), 2-10.

6) F. Roccaforte, A. Frazzetto, G. Greco, F. Giannazzo, P. Fiorenza, R. Lo Nigro, M. Saggio, M. Leszczyński, P. Pristawko and V. Raineri, "Critical issues for interfaces to p-type SiC and GaN in power devices", Appl. Surf. Sci., 258 (2012), 8324-8333.

7) S. N. Mohammad, "Contact mechanisms and design principles for alloyed ohmic contacts to n-GaN", J. Appl. Phys., 95 (2004), 7940-7953.

8) B. P. Luther, S. E. Mohney and T. N. Jackson, "Titanium and titanium nitride contacts to n-type gallium nitride", Semicond. Sci. Technol., 13 (1998), 1322-1327.

9) S. Nagasaki and M. Hirabayashi, "Phase diagrams of binary alloys", Agne Gijutsu Center (2004), 313, 二元合金状態図集.

10) K. Harafuji and K. Kawamura, "Sputtering Yield as a Function of Incident Ion Energy and Angle in Wurtzite-Type GaN Crystal", Jap. J. Appl. Phys., 47 (2008), 1536-1540.

11) M. Maeda, T. Yamasaki and Y. Takahashi, "Ohmic Contact Mechanism of Titanium-based electrodes on n-type Gallium Nitride", Trans. JWRI 41 No. 1 (2012), 45-48.

12) K. Kimura, M. Maeda and Y. Takahashi, "Effect of Argon Ion Irradiation on Ohmic Contact Formation on n-type Gallium Nitride", Mater. Trans. 54 No. 6 (2013), 895-898.