Journal of
Nanoscience and Nanotechnology
Vol. 13, 5715–5718, 2013

Ohmic Contacts to *N*-Face *p*-GaN Using Ni/Au for the Fabrication of Polarization Inverted Light-Emitting Diodes

Seung Cheol Han[1,†], Jae-Kwan Kim[1], Jun Young Kim[1], Dong Min Lee[1],
Jae-Sik Yoon[2,*], Jong-Kyu Kim[3], E. F. Schubert[4], and Ji-Myon Lee[1,*]

[1] *Department of Materials Science and Metallurgical Engineering, Sunchon National University, Sunchon, Jeonnam 540-742, Korea*
[2] *Division of Materials Science, Korea Basic Science Institute, Daejeon 305-333, Korea*
[3] *Department of Materials Science and Technology, POSTECH, Pohang 790-784, Korea*
[4] *Department for Electrical, Computer, and Systems Engineering, RPI, Troy, NY 12180, USA*

The electrical properties of Ni-based ohmic contacts to *N*-face *p*-type GaN were investigated. The specific contact resistance of *N*-face *p*-GaN exhibits a linear decrease from 1.01 Ω cm^2 to 9.05×10^{-3} Ω cm^2 for the as-deposited and the annealed Ni/Au contacts, respectively, with increasing annealing temperature. However, the specific contact resistance could be decreased down to 1.03×10^{-4} Ω cm^2 by means of surface treatment using an alcohol-based $(NH_4)_2S$ solution. The depth profile data measured from the intensity of O1s peak in the X-ray photoemission spectra showed that the alcohol-based $(NH_4)_2S$ treatment was effective in removing the surface oxide layer of GaN.

Keywords: *N*-Face *p*-GaN, LED, Surface Treatment, XPS.

1. INTRODUCTION

The group III nitrides including GaN are attractive materials for optoelectronic devices because of the success in commercialization of blue light emitting diodes (LEDs).[1–5] Generally, nitrides exhibit high spontaneous or piezoelectric polarization fields that are oriented along the *c* direction. This large polarization filed cause spatial separation of injected electrons and holes that results in reduced radiative recombination efficiency. To overcome these polarization effects in LEDs, devices grown on nonpolar or semipolar templates have been developed.

Furthermore, polarization inverted *p*-side down LEDs were also realized and showed only 10% efficiency droop up to 500 A/cm^2 by using hydride vapor epitaxy (HVPE).[6] However, fabrication of *p*-down LEDs were known to be difficult due to vulnerability for dry-etch damage of *p*-type GaN.

On the other hand, to obtain a low-resistance ohmic contact to *p*-type GaN, a variety of surface treatments of *p*-GaN using solutions such as aqua-regia solution,[7] and $(NH_4)_2S_x$,[8,9] have been proposed. It has been reported that the surface treatment with a $(NH_4)_2S_x$ solution is especially efficient in removing the native oxide layer on the *p*-type GaN surface, resulting in a low-resistance ohmic contact to *p*-type GaN.[9] In the area of GaAs devices, several studies have reported that the alcohol-based $(NH_4)_2S_x$ solution removes the native oxide on the GaAs surface more efficiently than the normal $(NH_4)_2S_x$ solution due to the low dielectric constant of the alcohol-based $(NH_4)_2S_x$ solution, resulting in a larger improvement in device characteristics.[10,11]

Zhilyaev et al.[12] have reported that the photoluminescence intensity of *n*-type GaN is considerably enhanced as a result of the surface treatment with an alcoholic sulfide solution. Our previous results[13] also showed that, for the case of *n*-type GaN, the surface treatment with an alcohol-based $(NH_4)_2S_x$ solution removes the insulating layer on the *n*-type GaN surface more effectively than the normal, $(NH_4)_2S_x$ solution, leading to more enhanced electrical properties. In this paper, we investigated the effect of an alcohol-based $(NH_4)_2S_x$ solution [t-$C_4H_9OH_1(NH_4)_2S$] on the characteristics of ohmic contacts to *N*-face *p*-type GaN.

2. EXPERIMENTAL DETAILS

The *p*-GaN samples were grown on a *c*-plane sapphire substrate by using a MOCVD system. After the growth of the GaN buffer layer and subsequent undoped GaN layer,

---

[*] Authors to whom correspondence should be addressed.
[†] Current address: Selcos Co. Suwon, 441-813, Korea.

1533-4880/2013/13/5715/004 doi:10.1166/jnn.2013.7072

2 um-thick *p*-GaN:Mg was grown. The GaN layers were rapid-thermal annealed at 650 °C for 1 min in N_2 ambient to activate the Mg dopant. Hall measurements showed that the carrier concentration was about 1×10^{17} cm^3. Using a KrF excimer laser (248 nm), a laser lift-off process was then performed to separate the sapphire substrate from the GaN layer, followed by HCl:DI (de-ionized) water (= 1:2) cleaning for 5 min to remove Ga droplets. The undoped GaN surface was then dry etched to a thickness of 1.7 um for inductively coupled plasma (ICP). The samples were first etched in HCl:H_2O (1:1) solution for 1 min and then dipped into alcoholic solution for 5 min at room temperature, which was composed of 90 vol% tert-butanol (t-C_4H_9OH) and 10 vol% $(NH_4)_2S$ before metal deposition. After the sulfur treatment, conventional photo resist mask was used for the fabrication of the circular transfer length method (CTLM) patterns. The size of the pads was 200×200 um^2 and the spacings between the pads were 10, 20, 40, 60, 80, and 100 um. The Ni (20 nm)/Au (80 nm) films were then deposited by electron-beam evaporation. Contact resistivity data were measured at room temperature using a parameter analyzer (HP4145B). To characterize the chemical bonding at the interface between the Ni layer and sulfur-treated *p*-type GaN, XPS was performed using the Mg Ka line (1253.6 eV) as an excitation source in a ultra-high-vacuum system.

3. RESULTS AND DISCUSSION

Figure 1(a) shows the specific contact resistance of the samples which had been deposited on *N*-face *p*-type GaN as a function of annealing temperatures. Specific contact resistances for the samples were determined from a plot of the measured resistance versus the spacings between the CTLM pads. The specific contact resistance was measured to be 1.01×10^0 Ω cm^2 for the untreated samples due to the high Schottky barrier height of surface state. As the annealing temperatures were increased to 300 °C, the specific contact resistance was also decreased to the value of 9.1×10^{-3} Ω cm^2. However, compared to the value of reported *N*-face *n*-type GaN sample and for the purpose of fabricating high efficiency LEDs, the specific contact resistance should be decreased further. We have tried the surface treatment method in order to quench the specific contact resistance and results are shown in Figure 1(b). By treating an alcohol-based $(NH_4)_2S$ solution to *N*-face *p*-type GaN, the specific contact resistance was decreased by four and by two orders of magnitude for untreated and 300 °C annealed sample, achieving 1.03×10^{-4} Ω cm^2 for the alcohol-based $(NH_4)_2S$ treated samples.

To study the mechanisms for the improvement of the ohmic characteristics, XPS spectra were obtained from the Ni/sulfur-treated *N*-face *p*-type GaN sample. Figure 2 shows the depth-profile data of Ga, Ni, O, C, and N peak from the Ni/GaN for untreated and alcohol-based $(NH_4)_2S$-treated samples, respectively.

As shown in Figure 2, the atomic percent of oxide for untreated sample is about 7% at the interface of Ni and GaN. However, atomic percent of O peak at the interface of the samples treated with alcohol-based $(NH_4)_2S$ solution were significantly decreased compared to that of the untreated sample, indicating that the treatment effectively remove the oxide layer at the interface.

It was known that the suitable surface treatment can effectively decrease the Schottky barrier height (SBH).

According to the metal semiconductor band theory[14, 15] the effective SBHs can be influenced by the presence of native oxide at the Ni/*p*-GaN interface, which can be described as,[15]

$$q\phi_b = q\phi_{b0} + 4\pi kT/h(2m\chi)^{1/2}\delta$$

where ϕ_{b0} is the SBH without native oxide. The second term is associated with the presence of an oxide layer, where m is the mean tunneling effective mass of the

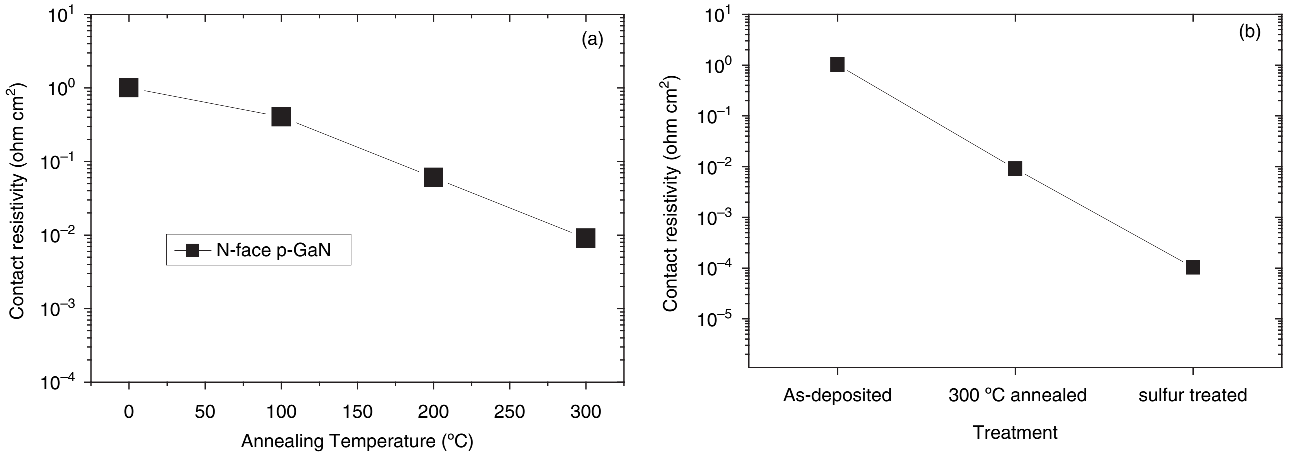

Fig. 1. Variation of contact resistivity for Ni (20 nm)/Au (80 nm) deposited on *N*-face *p*-type GaN as (a) a function of annealing temperatures and (b) surface treatment.

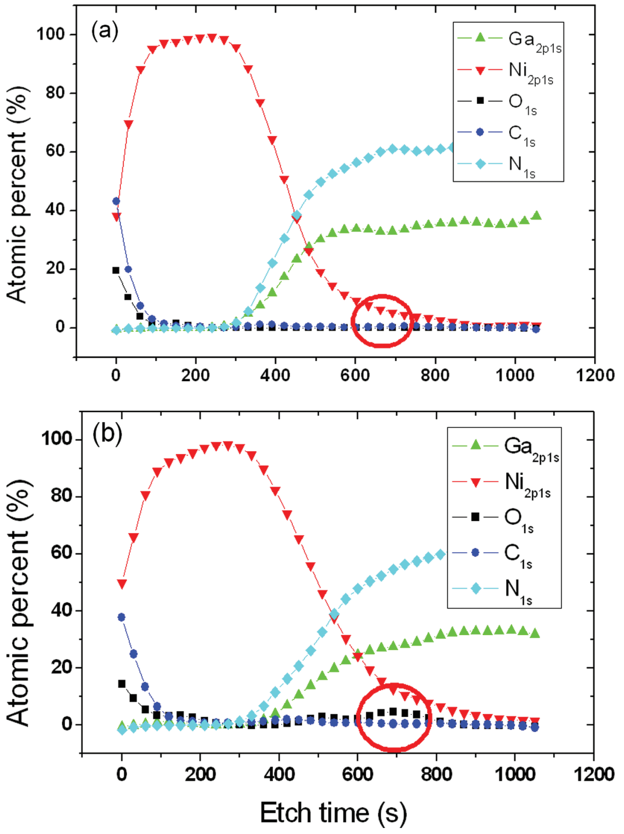

Fig. 2. XPS depth profiles of (a) untreated and (b) an alcohol-based $(NH_4)_2S$-treated *N*-face *p*-type GaN.

carriers, χ the mean tunneling barrier for carrier injection form a metal to a semiconductor, and δ the oxide layer thickness. This indicates that the effective removal of native oxide due to the surface treatment (Fig. 2) could make a contribution to the observed reduction of the SBHs due to the decreased δ. This result shows that the oxide layer was efficiently removed from the *N*-face *p*-GaN surface by the surface treatment with alcohol-based $(NH_4)_2S$ solution. In other words, increased barrier height for hole injection from metal to *p*-type GaN by formation of oxide layer could be reduced by treatment with the alcohol-based $(NH_4)_2S$ solution. Hence, the improved ohmic characteristics for samples can be attributed to the removal of the interfacial oxide layer.

Figure 3 shows the Ga2p peak in the Ni/GaN interface regions of the samples before and after the treatment. It is shown that the Ga2p core level of the treated sample shifts toward the lower binding energy side by 0.3 eV, compared to that of the untreated sample.

The position of surface Fermi level can be determined from the energy position of the Ga—N peaks in the core-level spectra. The difference between the Ga2p core-level binding energy and valence band maximum in bulk GaN is 1116.7 eV. Therefore, the following equation is used to determine the position of surface Fermi level:[16]

$$E_F = E_{\mathrm{Ga2p}} - 1116.7\ \mathrm{eV}$$

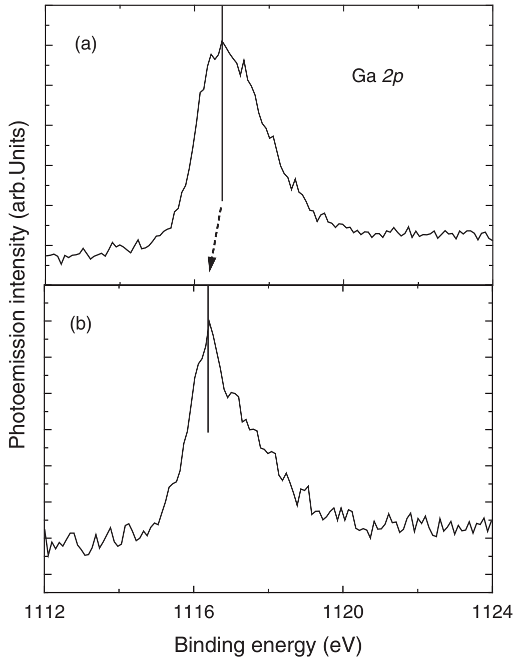

Fig. 3. Ga2p core-level spectra of the Ni/*N*-face *p*-type GaN interface for (a) an untreated sample and (b) an alcohol-based $(NH_4)_2S$-treated sample.

where E_F is surface Fermi level position relative to the valence band maximum and E_{Ga2p} core-level binding energy for Ga—N bonds.

This implies that the alcohol-based $(NH_4)_2S$-treated samples causes the surface Fermi level to shift toward the valence-band edge, resulting in a reduction in the band bending in the *p*-GaN. A previous study[17] reported that sulfur does not bond with nitrogen but bonds with gallium or occupies nitrogen-related vacancies.

The S ions in the solution would then bond to the Ga atoms on the *N*-face GaN sub-surface, producing Ga sulfides and this sulfides are soluble in the sulfur solution.[18] Hence, the simultaneous process of reaction and dissolution can leave a very thin sulfide layer on the sulfur-treated GaN surfaces, leading to the effective removal of surface oxide, formation of Ga vacancies, and protection from the formation of the native oxide on exposure to air prior to metal deposition.

Figure 4 shows the schematic energy band diagram of Ni/*p*-GaN ohmic contact to *N*-face *p*-type GaN. As the binding energy of Ga2p peak of surface treated sample shifted to valence-band, the valence-band maxima of the GaN also shifted to the Fermi level, resulting in the decrease of band bending between metal and GaN interface. According to this, the Schottky barrier height should be decreased as follows;

$$q\phi_p = E^{T}_{\mathrm{Ga2p}} - (E^{NT}_{\mathrm{Ga2p}} - E_V)$$

where $q\phi_p$ is SBH between Ni and *p*-GaN, and E^{T}_{Ga2p}, E^{NT}_{Ga2P}, and E_v is a binding energy of core-level spectrum

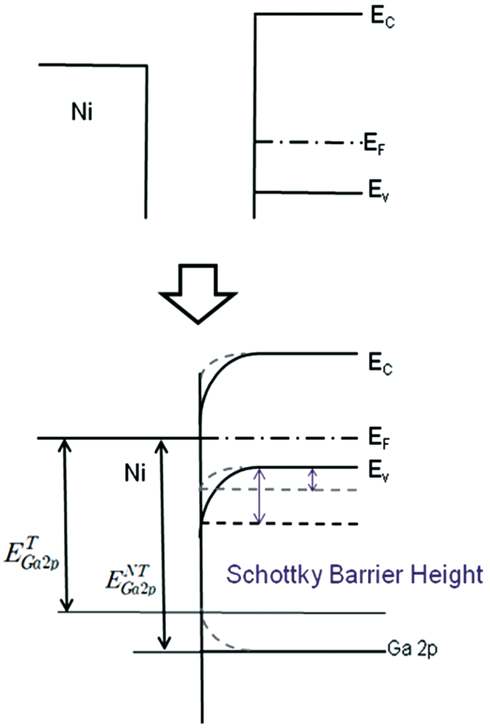

Fig. 4. Schematic energy band diagram of Ni/p-GaN ohmic contact.

for surface treated and non-treated sample, and valence band maxima, respectively. From these results, the reduced band-bending renders the decrease of effective SBH resulting in the enhanced transfer of holes between metal and valence band of GaN, indicating that the alcohol based $(NH_4)_2S$ treatment effectively enhance the ohmic contact properties of Ni/N-face p-type GaN.

4. CONCLUSION

We report on results about electrical properties of Ni-based ohmic contact on N-face p-type GaN. Contact resistance are decreased as the annealing temperature was increased. In order to lower a contact resistance further, alcohol-based $(NH_4)_2S$ surface treatment on N-face p-type GaN were conducted. Compared to the untreated sample, the specific contact resistance was drastically decreased by four orders of magnitude. The oxygen depth-profiling data showed that the alcohol-based $(NH_4)_2S$ treatment is very effective in the removal of the surface oxide layer. The Ga2p core-level peak for the alcohol-based $(NH_4)_2S$-treated sample showed a red-shift by 0.3 eV toward the valence-band edge compared to that for the untreated sample. The drastic improvement in the ohmic characteristics of the alcohol-based $(NH_4)_2S$-treated sample can be attributed to the effective removal of the surface oxide and the shift of the surface Fermi level toward the valence-band edge, resulting in the lowering of SBH.

Acknowledgment: This work was supported by the Ministry of Knowledge Economy (MKE) through the project of Regional Innovation Center (RIC) and by the Korea Basic Science Institute (KBSI) grant (T32604).

References and Notes

1. S. Nakamura, M. Senoh, N. Iwasa, and S. Nagahama, *Jpn. J. Appl. Phys*. 34, L797 (**1995**).
2. S. Nakamura, M. Senoh, S. Nagahama, Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, and Y. Sugimoto, *Jpn. J. Appl. Phys.* 35, L217 (**1996**).
3. M. A. Khan, A. R. Bhattarai, J. N. Kuznia, and D. T. Olson, *Appl. Phys. Lett*. 63, 1214 (**1993**).
4. M. A. Khan, J. N. Kuznia, A. R. Bhattarai, and D. T. Olson, *Appl. Phys. Lett*. 62, 1786 (**1993**).
5. M. A. Khan, J. N. Kuznia, D. T. Olson, J. M. Van Hove, M. Blasingame, and L. F. Reitz, *Appl. Phys. Lett*. 60, 2917 (**1993**).
6. M. L. Reed, E. D. Readinger, H. Shen, M. Wraback, and A. Syrkin, *Appl. Phys. Lett*. 93, 133505 (**2008**).
7. J. K. Kim, J. L. Lee, J. W. Lee, H. E. Shin, Y. J. Park, and T. Kim, *Appl. Phys. Lett*. 73, 2953 (**1998**).
8. J.-S. Jang, S.-J. Park, and T.-Y. Seong, *J. Vac. Sci. Technol. B* 17, 2667 (**1999**).
9. J.-L. Lee, J. K. Kim, J. W. Lee, Y. J. Park, and T. Kim, *Electrochem. Solid-State Lett*. 3, 53 (**2000**).
10. V. N. Bessolov, M. V. Lebedev, and D. R. T. Zahn, *J. Appl. Phys*. 82, 2640 (**1997**).
11. V. N. Bessolov, A. F. Ivankov, E. V. Konenkova, and M. V. Lebedev, *Tech. Phys. Lett.* 21, 20 (**1995**).
12. Y. V. Zhilyaev, M. E. Kompan, E. V. Konenkova, and S. D. Raevskii, *MRS Internet J. Nitride Semicond. Res.* 4S1, G6.14 (**1999**).
13. C. Huh, S.-W. Kim, H.-S. Kim, I.-H. Lee, and S.-J. Park, *J. Appl. Phys*. 87, 4591 (**2000**).
14. Y. E. H. Rhoderick and R. H. Williams, Metal-Semiconductor Contacts, Clarendon, Oxford, U.K. (**1998**).
15. K. Hattori and Y. Izumi, *J. Appl. Phys*. 53, 6906 (**1982**).
16. G. Landgren, R. Ludeke, Y. Jugnet, J. F. Morar, and F. J. Himpsel, *J. Vac. Sci. Technol. B* 2, 351 (**1984**).
17. Y.-J. Lin, C.-D. Tsai, Y.-T. Lyu, and C.-T. Lee, *Appl. Phys. Lett*. 77, 687 (**2000**).
18. R. C. Weast, M. J. Astle, and W. H. Beyer (eds.), Handbook of Chemistry and Physics, 64th edn., CRC, New York (**1985**).

Received: 23 March 2012. Accepted: 4 May 2012.