Journal of the Korean Physical Society, Vol. 51, No. 1, July 2007, pp. 159∼162

High-Transmittance NiSc/Ag/ITO p-Type Ohmic Electrode for Near-UV GaN-Based Light-Emitting Diodes

Hyun-Gi Hong, Hyunseok Na and Tae-Yeon Seong*
Division of Materials Science and Engineering, Korea University, Seoul 136-713

Takhee Lee
Department of Materials Science and Engineering,
Gwangju Institute of Science and Technology, Gwangju 500-712

June O Song and Kyung-Kook Kim
Photonics Project Team, Samsung Advanced Institute of Technology, Suwon 440-600

(Received 26 March 2007)

We report on the formation of NiSc(2.5 nm)/Ag(2.5 nm)/ITO(200 nm) transparent *p*-type Ohmic electrodes for GaN-based near-UV light-emitting diodes (LEDs). We show that the NiSc(2.5 nm)/Ag(2.5 nm)/ITO(200 nm) contacts become Ohmic with contact resistivity of 4.9×10^{-3} Ωcm^2 and a transmittance of 80 % at 400 nm when annealed at 630 °C for 1 min in air. Near-UV (400 nm) LEDs fabricated with the annealed NiSc/Ag/ITO *p*-contacts give a forward-bias voltage of 3.69 V at 20 mA and a series resistance of 21.1 Ω, which are better than those for Ni/Au contacts. Based on Auger electron spectroscopy and electrical results, possible Ohmic formation mechanisms are described.

PACS numbers: 72.80.Ey, 73.40.Cg, 73.20.At
Keywords: LED, *p*-type Ohmic contact, Transmittance, Contact resistivity

I. INTRODUCTION

GaN-based semiconductors are of technological importance for their applications in blue light-emitting diodes (LEDs) and laser diodes. Formation of low resistance and thermally stable Ohmic contacts is one of the important processing factors for the fabrication of such high-performance devices [1,2]. In particular, for GaN-based LEDs, transparent conducting oxides (TCOs) are commonly used for *p*-type contacts due to their good transparency with moderate sheet resistance [3–5]. Among them, indium tin oxide (ITO) is most commonly used because of its high transmittance (∼90 % in the visible range) and low resistivity (∼10^{-4} Ω-cm). However, single ITO contacts to *p*-GaN do not produce good Ohmic contacts [3]. Thus, ITO is usually used with thin metal interlayers to form good Ohmic contacts to *p*-GaN. For example, several groups have investigated various ohmic schemes such as Ag/ITO, Ag/SnO_2, Ni/ITO, Ni/ZnO, Ni/Au/ITO, Ni/Au/ZnO, and Ni/Ag/ITO [4–10]. These schemes showed improved optical properties compared with the commercially being used Ni/Au contacts. For example, Song *et al.* [10], investigating the electrical performance of near-UV GaN-based LEDs fabricated with Ni/Ag/ITO *p*-type contacts, showed that LEDs with the Ni/Ag/ITO contacts gave much improved reverse leakage current characteristics compared to LEDs with Ag/ITO contacts. It was also shown that the output power of LEDs with Ni/Ag/ITO contacts was enhanced by 34 % compared with that of LEDs made without the Ni interlayer.

In this work, to further improve the performance of LEDs fabricated with Ni/Ag/ITO contacts, we used NiSc layers instead of Ni. In other words, NiSc(2.5 nm)/Ag(2.5 nm)/ITO(200 nm) contacts are investigated as a *p*-type ohmic scheme for use in near-UV LEDs. Sc is expected to play an important role in improving the optical properties of NiSc-based contacts when annealed in air, because Sc-oxide is one of the frequently used materials in UV range anti-reflection coatings due to its high refractive index (n = 2.15) [11,12]. The NiSc/Ag/ITO contacts are shown to become Ohmic with a specific contact resistance of 4.9×10^{-3} Ωcm^2 and to give a transmittance of 81 % at a wavelength of 400 nm when annealed at 630 °C for 1 min in air. Near UV-LEDs (400 nm) fabricated with annealed NiSc/Ag/ITO contacts are also characterized.

*E-mail: tyseong@korea.ac.kr; Fax: +82-2-928-3584

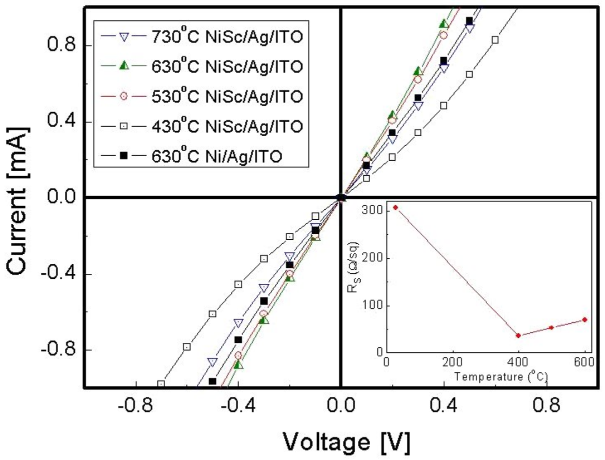

Fig. 1. Typical I-V characteristics of the NiSc/Ag/ITO and the Ni/Ag/ITO contacts as functions of the annealing temperature, as measured on 4-μm-spaced pads.

II. EXPERIMENTS

1.0 μm-thick Mg-doped GaN layers ($N_a = 5 \times 10^{17}$ cm^{-3}) were grown by using metal-organic chemical vapor deposition. The samples were then ultrasonically degreased using trichloroethylene, acetone, methanol, and deionized water for 5 min in each step, followed by N_2 blowing. Prior to photolithography, the samples were treated with a buffered oxide etch (BOE) solution for 20 min and rinsed in DI water. Circular transfer length method (CTLM) patterns were defined by using the standard photolithographic technique for measuring the specific contact resistance. The inner dot radius was fixed at 120 μm, and the spacing between the inner and the outer radii was varied from 4 to 24 μm. NiSc(2.5 nm)/Ag(2.5 nm)/ITO(200 nm) layers were electron-beam evaporated using a NiSc target containing 10 at % Sc. For comparison, Ni(2.5 nm)/Ag(2.5 nm)/ITO(200 nm) and Ni(5 nm)/Au(5 nm) layers were also prepared. Some samples underwent rapid thermal annealing at temperatures of 430 – 730 °C for 1 min in air 2.0.

Current-voltage (I-V) measurements were performed using a parameter analyzer (HP 4155A), and transmittance measurements were done using a high-resolution UV-VIR-NIR spectrophotometer (Varian Cary 1E, HP 8452A diode-array spectrometer). To investigate interfacial reactions, we used Auger electron spectroscopy (AES, PHI670).

III. RESULTS AND DISCUSSION

Figure 1 shows typical I-V characteristics of NiSc/Ag/ITO and Ni/Ag/ITO contacts as functions of the annealing temperature. The as-deposited sample shows non-linear I-V characteristics. However, as the annealing temperature increases, their I-V characteristics

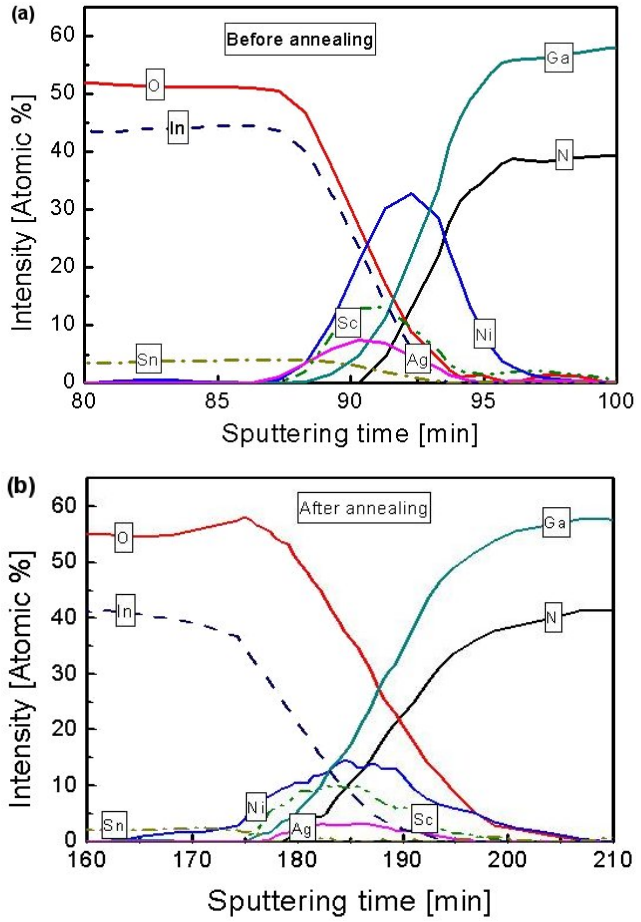

Fig. 2. AES depth profiles of the NiSc/Ag/ITO contacts (a) before and (b) after annealing at 630 °C for 1 min in air.

become improved. In particular, the sample annealed at 630 °C shows the best I-V characteristics, which is better than that of the Ni/Ag/ITO contacts annealed at 630 °C. It is, however, noted that the 730 °C-annealed sample exhibits slightly degraded electrical behavior. The specific contact resistance was determined from the plots of the measured resistance versus the spacing between the CTLM pads [13]. The least-squares method was used to fit a straight line to the experimental data. Measurements showed that the NiSc/Ag/ATO contacts produced a specific contact resistance of 4.9×10^{-3} Ωcm^2 upon annealing at 630 °C.

Figure 2 shows the AES depth profiles of the NiSc/Ag/ITO contacts before and after annealing at 630 °C. For the as-deposited sample (Figure 2(a)), individual layers are well defined, indicating insignificant intermixing between the contact schemes and the GaN. For the annealed sample (Figure 2(b)), however, some amount of Ag was indiffused towards the GaN. It is noted that some amount of oxygen indiffused into the interface region from the annealing gas. The fact that Sc-oxide has a heat of formation of –1918 kJ/kmole and nickel oxide has a heat of formation of –239 kJ/kmole indicates the

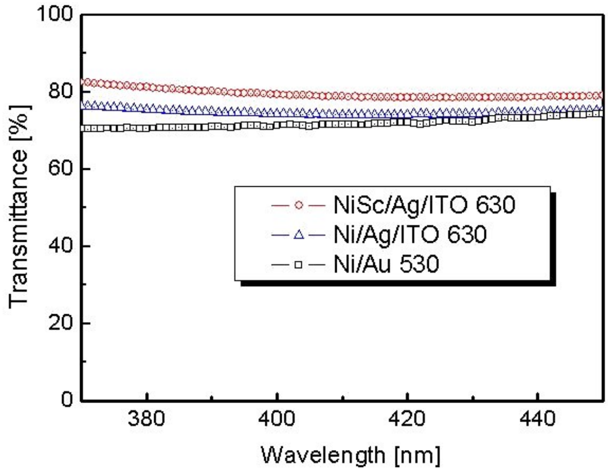

Fig. 3. Transmittance of the 630 °C-annealed NiSc/Ag/ITO, 630 °C-annealed Ni/Ag/ITO, and 530 °C-annealed Ni/Au contacts, all annealed for 1min in air.

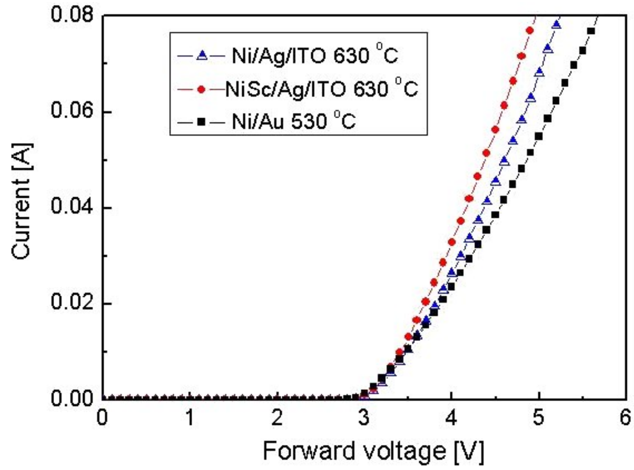

Fig. 4. I-V characteristics of near-UV LEDs (400 nm) fabricated using different *p*-type electrodes, all annealed for 1 min in air.

formation of Sc-oxide (and/or perhaps Ni-oxide) [14,15]. In addition, some amount of Ga seems to outdiffuse into the contact layer. This implies possible reactions between Ag and Ga and between Ni and Ga, leading to the formation of a Ag-Ga solid-solution and/or a Ni-gallide phase near the interface region.

Optical property measurements were carried out by depositing *p*-type contact layers on the glass substrate. Figure 3 shows the transmittance of the 630 °C-annealed NiSc/Ag/ITO, 630 °C-annealed Ni/Ag/ITO, and 530 °C-annealed Ni/Au contacts. The annealed NiSc/Ag/ITO contacts gave higher transmittances than the annealed Ni/Ag/ITO and Ni/Au contacts across the whole wavelength region of 370 – 450 nm. For example, the transmittances of the annealed NiSc/Ag/ITO, Ni/Ag/ITO, and Ni/Au contacts were measured to be 80, 74, and 69 % at 400 nm, respectively.

Figure 4 shows the I-V characteristics of near-UV LEDs (400 nm) fabricated with different *p*-type Oohmic electrodes. The LEDs with the 630 °C-annealed NiSc/Ag/ITO contacts gave better I-V characteristics than those with 630 °C-annealed Ni/Ag/ITO and the 530 °C-annealed Ni/Au contacts. For example, the LEDs made with the NiSc/Ag/ITO contacts produced a forward-bias voltage of 3.69 V at an injection current of 20 mA and a series resistance of 21.1 Ω, whereas the LEDs with the Ni/Ag/ITO and the Ni/Au contacts gave 3.81 and 3.87 V at 20 mA and series resistances of 23.7 and 29.8 Ω, respectively.

The annealing-induced improvement of the electrical properties of the NiSc/Ag/ITO contacts may be explained as follows: First, the improvement could be related to the electrical nature of ITO. In other words, a resistive amorphous ITO film became crystallized and conductive when annealed at temperatures above 530 °C. Second, it could be associated with the formation of a Ag-Ga solid solution and a Ni-gallide phase, as noted from the AES data. The formation of a Ag-Ga solid solution and a Ni-gallide phase generates deep acceptor-like Ga vacancies near the interface between the contact and the GaN. This leads to an increase in the carrier concentration near the GaN surface and hence, a reduction in the contact resistivity [16–19]. Third, the improvement might be related to the formation of inhomogeneous barriers at the contact scheme/GaN interface due to the breaking-up of the NiSc/Ag thin films near the interface. It is well known that metal and/or TCO thin films inserted between GaN and Ag or ITO layers are readily broken into nano-particles when annealed in air, leading to the formation of interfaces with inhomogeneous Schottky barriers [10, 20]. According to the electronic transport theory at the metal/semiconductor interface with inhomogeneous Schottky barriers [20], the presence of nano-dots and a difference of the Schottky barrier heights between nano-dots and GaN could result in an increase in the electric field at the MS interface. An increase in the electric field was found to cause a lowering of the barrier height, and as a result, a reduction of specific contact resistance [5,22–24]. Thus, the combined effects of the three could be responsible for the improved electrical properties of the annealed NiSc/Ag/ITO *p*-contacts.

IV. SUMMARY

We have investigated NiSc/Ag/ITO layers to obtain low resistance and (in particular) highly transparent Ohmic contacts to *p*-GaN for high performance UV LEDs. We showed that the NiSc(2.5 nm)/Ag(2.5 nm)/ITO(200 nm) contacts yielded Ohmic behavior with a specific contact resistance of 4.9×10^{-3} Ωcm^2 and a transmittance of 80 % at a wavelength of 400 nm after annealing at 630 °C for 1 min in air. In addition, near UV-LEDs fabricated with the 630 °C-annealed

NiSc/Ag/ITO contacts produced better I-V characteristics compared with those fabricated with the annealed Ni/Ag/ITO and Ni/Au contacts. These results indicate that the NiSc/Ag/ITO contacts may serve as a potentially important scheme for the fabrication of high-performance near-UV LEDs.

ACKNOWLEDGMENTS

This work was supported by the basic research program of the Korea Science & Engineering Foundation (Grant no. R01-2006-000-10904-0).

REFERENCES

[1] S. W. Chae, J. S. Kwak, S. K. Yoon, M. Y. Kim, J. O. Song and T. Y. Seong, T. G. Kim, J. Korean Phys. Soc. **9**, 899 (2006).
[2] J. S. Kwak, J. Cho and C. Sone, J. Korean Phys. Soc. **48**, 1259 (2006).
[3] T. Margalith, O. Buchinsky, D. A. Cohen, A. C. Abare, M. Hansen, S. P. Denbaars and L. A. Coldren, Appl. Phys. Lett. **74**, 3930 (1999).
[4] J. O. Song, K. K. Kim, S. J. Park and T. Y. Seong, Appl. Phys. Lett. **83**, 479 (2003).
[5] J. O. Song and T. Y. Seong, Appl. Phys. Lett. **85**, 6374 (2004).
[6] J. O. Song, D. S. Leem, J. S. Kwak, Y. Park, S. W. Chae and T. Y. Seong, Photon. Technol. Lett. **17**, 291 (2005).
[7] S. M. Pan, R. C. Tu, Y. M. Fan, R. C. Yeh and J. T. Hsu, Photon. Technol. Lett. **15**, 646 (2003).
[8] S. Y. Kim, H. W. Jang and J. L. Lee, Appl. Phys. Lett. **82**, 61 (2003).
[9] S. P. Jung, D. Ullery, C. H. Lin, H. P. Lee, J. H. Lim, D. K. Hwang, J. Y. Kim, E. J. Yang and S. J. Park, Appl. Phys. Lett. **87**, 181107 (2005).
[10] J. O. Song, H. Kang, I. T. Ferguson, S. P. Jung, H. P. Lee, H. G. Hong and T. Y. Seong, Solid State Electron. **49**, 1986 (2005).
[11] M. F. Ali-Kuhaili, Thin Solid Films **426**, 178 (2003).
[12] Z. Xu, A. Daga and H. Chen, Appl. Phys. Lett. **79**, 3782 (2001).
[13] G. S. Marlow and M. B. Das, Solid State Electron. **25**, 91 (1982).
[14] G. V. Samsonov, *The Oxide Handbook*, 2nd ed., (IFI/ Plenum Data Company, New York, 1982), p. 20.
[15] A. Shih, J. E. Yater, C. Hor and R. Abrams, Appl. Surf. Sci. **211**, 136 (2003).
[16] J. O. Song, D. S. Leem and T. Y. Seong, Appl. Phys. Lett. **83**, 3513 (2003).
[17] J. S. Jang, S. J. Park and T. Y. Seong, J. Vac. Sci. Technol. B **17**, 2667 (1999).
[18] V. M. Bermudez, D. D. Koleske and A. E. Wickenden, Appl. Surf. Sci. **126**, 69 (1998).
[19] J. O. Song, J. S. Kwak, Y. Park and T Y. Seong, Appl. Phys. Lett. **86**, 062104 (2005).
[20] K. Y. Ban, H. G. Hong, D. Y. Noh, T. Y. Seong, J. O. Song and D. Kim, Semicond. Sci. Technol. **20**, 921 (2005).
[21] R. T. Tung, Phys. Rev. B **45**, 13509 (1992).
[22] S. K. Lee, C. M. Zettering, M. Ostling, I. Aberg, M. H. Magnusson, K. Deppert, L. E. Wernersson, L. Samuelson and A. Litwin, Solid State Electron. **46**, 1433 (2002).
[23] E. H. Rhoderick and R. H. Williams, *Metal-Semiconductor Contacts* (Clarendon, Oxford, 1988), p. 39.
[24] J. I. Sohn, J. O. Song and D. S. Leem, S. Lee and T. Y. Seong, Electrochem. Solid-State Lett. **7**, G179 (2004).