Journal of Optoelectronics and Advanced Materials Vol. 6, No. 1, March 2004, p. 177 - 182

LOW-RESISTANCE OHMIC CONTACTS TO N-TYPE GaN USING Ti/Al/Re/Au MULTILAYER SCHEME

V. Rajagopal Reddy*, C. K. Ramesh

Department of Electronics, University of Mysore, Post-Graduate Centre, Hemagangotri, Hassan – 573 220, India

A Ti/Al/Re/Au multilayer scheme has been developed for obtaining very low ohmic contact to moderately doped n-type GaN (4.07×10^{18} cm^{-3}). It is shown that the I-V characteristics of the as-deposited contacts improved upon annealing temperatures in the range of 550–750 °C. Specific contact resistance as low as 1.3×10^{-6} Ωcm^2 is obtained from the Ti (150Å)/Al (600Å)/ Re (200Å)/ Au (500Å) contact annealed at 750 °C for 1min in a N_2 ambient. It is also shown that annealing results in a large reduction (by ~150 meV) in the Schottky barrier heights of contact, compared to the as-deposited one. Based on the XPS and AES results, possible explanations for the annealing temperature dependence of the specific contact resistance of the Ti/Al/Re/Au contacts are described and discussed.

(Received January 7, 2004; accepted February 19, 2004)

Keywords: Ohmic Contacts, n-type GaN, Schottky barrier height, X-ray photoelectron spectroscopy, Auger electron microscopy

1. Introduction

Gallium nitride (GaN) is highly attractive material for making blue light sources [1,2], high-power microwave devices [3] and high-temperature electronic devices [4]. The various difficulties in achieving high performance GaN-based devices are the need to form ohmic contacts with very low resistance, smooth morphology and thermal stability for reliable high temperature performance. These factors are critical to the fabrication of short channel electronic devices, namely, high-electron mobility transistors (HEMTs) and metal-semiconductors field effect transistors (MESFTs).

A number of ohmic contact systems have been reported for n-type GaN [5-9]. Among them, the Ti/Al system has become the conventional widely used ohmic contact [8,9]. Rapid thermal annealing at temperature as high as 900 °C in N_2 or Ar ambient is widely used for alloying these bilayer contacts. However, due to the Al propensity for oxidation, Al-based contacts have severe reliability limitations when subjected to high temperature processing or when operating under high temperature conditions. In previous studies [10], metals such as Ni and Au, which are resistant to oxidation, were placed on the top of the Ti/Al contacts to prevent the oxidation of the contacts during alloying. Some of the multilayer ohmic contacts e.g., Ti/Al/Ti/Au, Ti/Al/Pd/Au, Ti/Al/Pt/Au, V/Al/Pt/Au and Ti/Al/Mo/Au have also been reported [11-16]. In general, high melting point metals exhibit lower-bulk diffusivities [17]. Re has significantly higher melting point than ethier Ni or other potential diffusion barriers such as Ti, Pd, Pt and Mo. In the present work, we investigate the Ti/Al/Re/Au scheme for use fabricating low resistance ohmic contacts to n-GaN (4.07×10^{18} cm^{-3}). It is shown that the Ti/Al/Re/Au contacts produce specific contact resistance as low as 1.3×10^{-6} Ωcm^2 when annealed at 750 °C for 1 min in a N_2 ambient.

* Corresponding author: dr_vrg@rediffmail.com

2. Experimental details

For the present study, n-GaN layers were grown by metalorganic chemical vapor deposition on c-plane sapphire substrate. An undoped GaN layer with a thickness of 2 μm was grown, followed by the growth of a 2 μm-thick n-GaN:Si (n_d = 4.07 × 10^{18} cm^{-3}) layer. The n-GaN layer was first ultrasonically degreased with trichloroethylene, acetone and methanol for 5 min in each step and then the surface oxides were removed in buffered oxide etch (BOE) solution for 10 min followed by a deionized water rinse and a dry N_2 blow. The CTLM pads were then patterned on the surface treated n-GaN layer using standard photolithography technique. The inner dot radius was 105 μm and the spacing between the inner and the outer radii were varied from 3 to 21 μm. Prior to metal deposition, the patterned layer was dipped in buffered oxide etch (BOE) solution for 1min, blown dry with N_2 gas, and immediately loaded into an electron beam evaporation system. A metal contact layer structure of Ti/Al/Re/Au (150Å /600 Å/200Å / 500Å) was then deposited on the surface treated n-GaN. Some of the samples were annealed at temperatures of 550 °C, 650 °C, and 750 °C for 1 min under N_2 ambient in a rapid thermal annealing system. Current and voltage characteristics (I-V) were measured using a semiconductor parameter analyzer (HP4155A). X-ray photoelectron spectroscopy (XPS) was employed to find the change of surface characteristics before and after annealing. Auger depth profiling was carried out to observe the extent of interdiffusion between the metal layers and the n-GaN.

3. Results and discussion

Fig. 1 shows the current-voltage characteristics of Ti/Al/Re/Au multilayer ohmic contacts on n-GaN as a function of annealing temperature, measured between the CTLM pads with a spacing of 3 μm. The as-deposited Ti/Al/Re/Au contact exhibits non-linear behaviour, which is probably due to the formation of rectifying Schottky contact, as evident from Fig.1. However, the contacts showed ohmic behavior after annealing at 550 °C for 1 min in nitrogen ambient. The specific contact resistance (ρc) was extracted from a least-square fit of the measured total resistance (Rt) versus the spacings between the CTLM pads. Measurement showed that the specific contact resistance is 1.3 × 10^{-6} Ωcm^2 for the sample annealed at 750 °C. The contacts Ti/Al/Re/Au on n-GaN showed best I-V characteristics after annealing at 750 °C for 1 min, Fig. 1. Thus, the as-deposited and 750 ˚C samples were mainly characterized in this work.

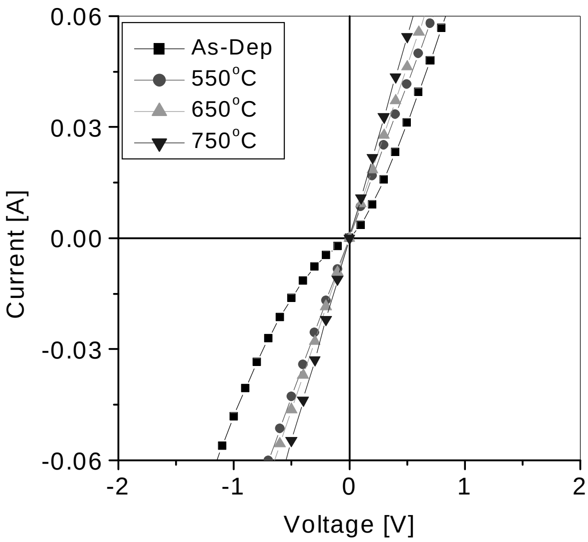

Fig. 1. The typical I-V characteristics for the Ti/Al/Re/Au (150Å /600 Å/200Å /500Å) contacts on n-type GaN as a function of the annealing temperature.

To determine the effective Schottky barrier heights (SBHs) of the contacts, I-V method [18, 19] was employed. The I-V relation is given by

$$I = I_o \exp(qV/nkT)[1-\exp(-qV/kT)] \quad (1)$$

$$I_o = AA^{**}T^2 \exp(-\phi_b/kT) \quad (2)$$

Where q is the electron charge, n the ideality factor, k the Boltzman constant, T the absolute temperature, A the contact area, A** the Richardson constant, ϕ_b the Schottky barrier height. The effective mass of electrons in GaN is m* = 0.22 m_o [20], which gives A^{**}= 26.4 A/cm^{2}K^2. Thus, a value of 26.4 A/cm^{2}K^2 was used for A** to calculate SBHs. Fig. 2 show plot of I/[1-exp (-qV/kT)] vs. V for the contacts. Calculations showed that the SBH is 0.46 (± 0.006) eV for the as-deposited sample and 0.31 (± 0.010) eV for the sample annealed at 750 ºC. It is shown that annealing treatment gives rise to a large reduction (by ~150 meV) in the SBH for the Ti/Al/Re/Au contact, compared with that of the as-deposited one.

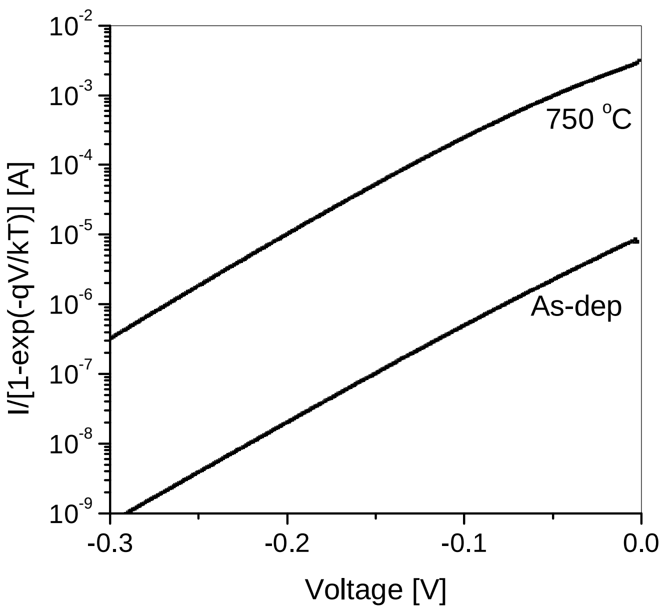

Fig. 2. Plot of I/[1-exp (-qV/kT)] vs. V for the Ti/Al/Re/Au contacts.

To investigate a shift of the surface Fermi level due to annealing treatment, XPS analysis was performed. The Ga 2p core level XPS spectra for the Ti/n-GaN interfaces before and after annealing at 750 ºC is shown in Fig. 3. For the annealed sample, the Ga 2p core level shifts toward the high-binding energy side, compared to the as-deposited one. For instance, the Ga 2p core level of annealed at 750 °C contact underwent a shift of 0.71 eV. This indicates that the annealing causes a shift of the surface Fermi level toward the conduction-band edge [21,22], resulting in a reduction of the surface-barrier height to n-GaN.

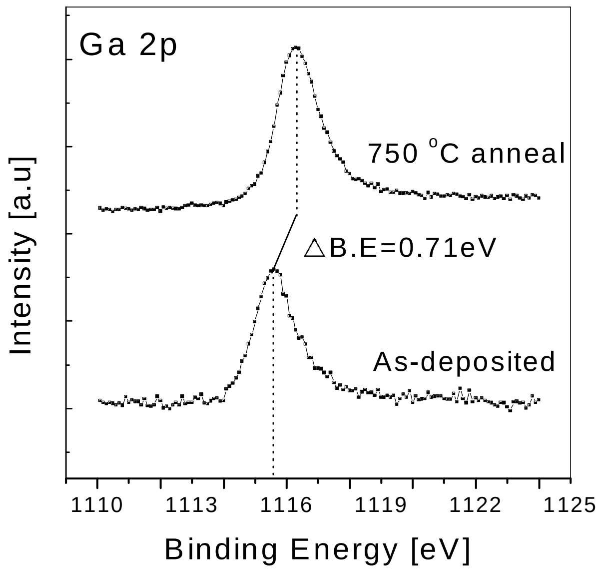

Fig. 3. Photoemission spectra of the Ga 2p core-level of Ti/n-GaN samples. It is noted that the Ga 2p core-level of the samples annealed at 750 ºC shifts towards the higher-binding energy side as compared with that of the as-deposited one.

Fig. 4 shows the Auger depth profiles of the Ti/Al/Re/Au contacts on n-GaN before and after annealing. For the as-deposited sample, there is no obvious evidence for interdiffusion between the metal layers and the n-GaN, Fig. 4(a). For the 750 °C sample, Fig. 4(b), there is significant intermixing between the metal layers. In addition, a large amount of nitrogen outdiffused into the metal layers. The AES depth profiles show extensive reactions between Ti, Al and GaN, resulting in the formation of the Ti- and Al-N phases at the interface. However, there is no clear evidence for the outdiffusion of Ga into the metal layers, indicating that interfacial layers formed on the GaN surface region may prevent the outdiffusion of Ga.

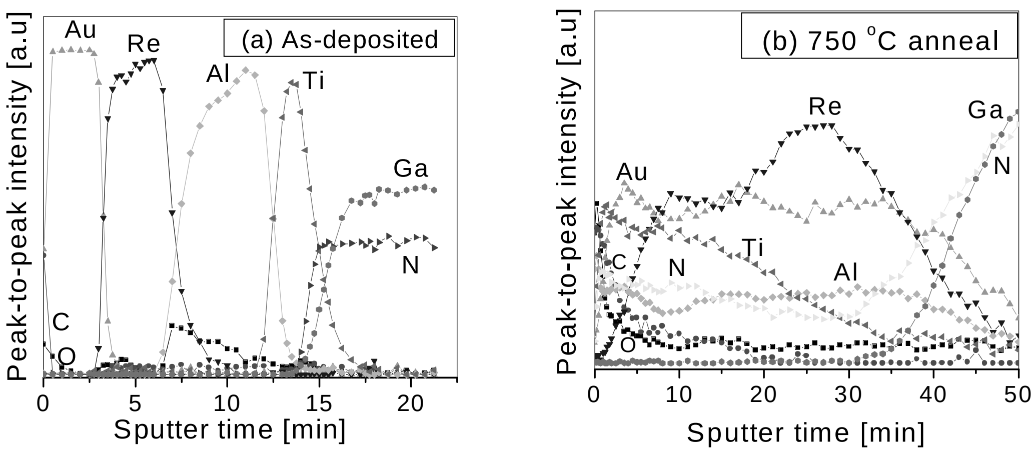

Fig. 4. AES depth profiles of the Ti/Al/Re/Au ohmic contacts to n-GaN before and after annealing: (a) as-deposited, and (b) annealed at 750 °C.

Based on the XPS and AES results, the annealing dependence of ohmic behaviour of the Ti/Al/Re/Au contacts could be explained as follows. First, the improvement can be related to the shift of surface Fermi level, as noted from the high-energy shift of the Ga 2p core level (Fig. 3), resulting in a reduction in the surface barrier height. The shift of the surface Fermi level could be caused by an increase in carrier concentration near the GaN surface region. The AES results showed that AlN and Ti-nitride phases were formed in the annealed samples. The formation of nitrides accompanied the generation of nitrogen vacancies causing heavy doping of GaN, the effective barrier height was thinned (see Fig. 5), and hence, the current conduction in the form of tunneling was facilitated through the junction. Nitrogen vacancies have been known to act as donors in GaN [23,24]. Thus, an increase in the carrier concentration near the surface of the n-GaN layer could in part contribute to the improvement of the I-V characteristics of the contacts. Similar finding was also observed by Luther et al [25] and Dimitriadis et al [26]. Luther et al [25] investigated Ti-based contacts to n-GaN and reported that the formation of TiN at the metal/GaN interface, resulting in the generation of nitrogen vacancies, is necessary for ohmic contact formation. Second, the reduced contact resistance may also be related to an increase in the contact area between the contact schemes and the GaN due to the interfacial reactions.

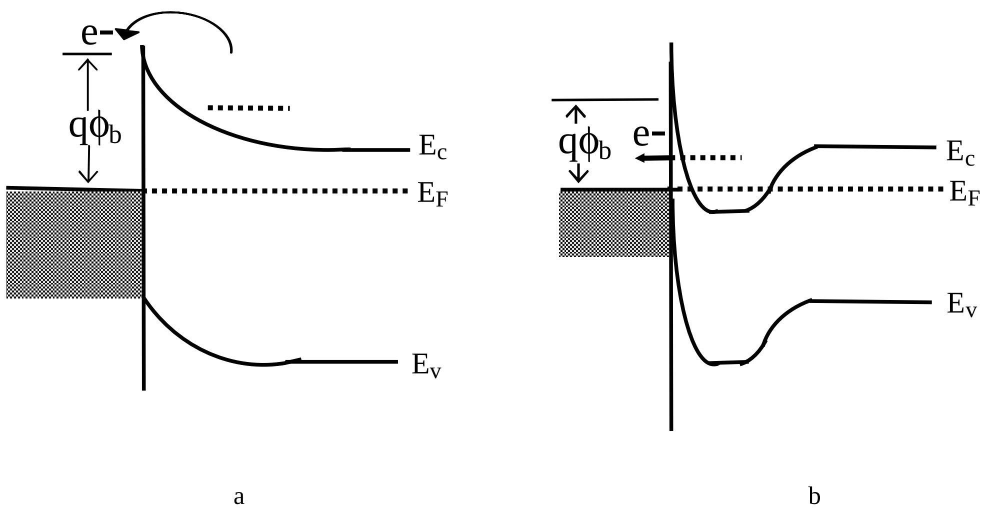

Fig. 5. Schematic energy-band diagram for the metal-semiconductor interface showing the band bending due to the presence of nitrogen vacancies V_N: (a) conduction and valence bands without band bending, and (b) conduction and valence bands with band bending due to the presence of nitrogen vacancies.

4. Conclusion

To summarise, a Ti (150Å)/Al (600Å)/Re (200Å)/Au (500Å) multilayer ohmic contacts on moderately doped n-type GaN (4.07×10^{18} cm^{-3}) have been investigated. A good ohmic contact with a specific contact resistance as low as 1.3×10^{-6} Ωcm^2 was obtained when the sample was annealed at 750 °C for 1 min in N_2 ambient. The effective SBHs determined by the I-V method was in the range of 0.46 – 0.31 eV for the as-deposited and annealed at 750 ºC, respectively. It is noteworthy that annealing results in a large reduction (by ~150 meV) in the Schottky barrier height of contact, compared to the as-deposited one. Based on the XPS and AES results, the temperature dependence of specific contact resistance was explained in terms of the combined effects of the shift of the surface Fermi level towards the conduction-band edge and of an increase of the contact area. The facts that the Ti/Al/Re/Au ohmic contact scheme produces very low specific contact resistance at high temperatures indicate that the scheme may suitable for high-temperature GaN-based device applications.

Acknowledgements

The authors thank to University Grant Commission (UGC), New Delhi for providing financial assistance (Grant No. F.14-22/2002 (SR-I)).

References

[1] S. Nakamura, T. Mukai, S. Senoh, Jpn. J. Appl. Phys. **30**, L1998 (1991).
[2] H. Amano, M. Kito, X. Hiramatsu, I. Akasaki, Jpn. J. Appl. Phys. **28**, L2112 (1998).
[3] H. Morkoc, S. Strite, G. B. Gao, M. E. Lin, B. Serdlov, M. Burns, J. Appl. Phys. **76**, 1363 (1994).
[4] M. A. Khan, M. S. Shur, Q. Chen, Appl. Phys. Lett. **68**, 3022 (1996).
[5] C. T. Lee, M. Y. Yeh, C. D. Tsai, Y. T. Lyu, J. Electron. Mater. **26**, 262 (1997).
[6] Q. Z. Liu, S. S. Lau, Solid-State Electron. **42**, 677 (1998).
[7] S. J. Pearton, J. C. Zolper, R. J. Shul, F. Ren, J. Appl. Phys. **86**, 1 (1999).
[8] M. E. Lin, C. Ma, F. Y. Huang, Z. F. Fan, L. H. Allen, H. Morkoc, Appl. Phys. Lett. **64**, 1003 (1994).
[9] B. P. Luther, S. E. Mohney, T. N. Jackson, M. A. Khan, Q. Chen, J. W. Yang, Appl. Phys. Lett. **70**, 57 (1997).
[10] Z. Fan, S. N. Mohammad, W. Kim, O. Aktas, A. E. Botchkarev, H. Morkoc, Appl. Phys. Lett. **68**, 1672 (1996).
[11] D. F. Wang, F. Shiwei, C. Lu, A. Motayed, M. Jah, S. N. Mohammad, K. A. Jones, L. S. Riba, J. Appl. Phys. **89**, 6214 (2001).
[12] E. F. Chor, D. Zhang, H. Gong, G. L. Chen, T. Y. F. Liew, J. Appl. Phys. **90**, 1242 (2001).
[13] S. J. Cai, R. Li, Y. L. Chen, L. Wong, W. G. Wu, S. G Thomas, K. L.Wang, Electron. Lett. **34**, 2354 (1998).
[14] C. T Lee, H. W. Kao, Appl. Phys. Lett. **76**, 2364 (2000).
[15] K. O. Schweitz, P. K Wang, S. E. Mohney, Appl. Phys. Lett. **80**, 1954 (2002).
[16] V. Kumar, L. Zhou, D. Selvanathan, I. Adesida, J. Appl. Phys. **92**, 1712 (2002).
[17] P. Shewmon, Diffusion in Solids, 2nd ed. (TMS Press, Warrendale, PA, 1989).
[18] T. Mori, T. Lozawa, T. Ohwaki, Y. Taga, S. Nagai, S. Yamasaki, S. Asami, N. Shibata, M. Koike, Appl. Phys. Lett. **69**, 3637 (1996).
[19] J. S. Jang, D. J. Kim, S. J. Park, T. Y. Seong, J. Electron. Mater. **30**, 94 (2001).
[20] M. Drechsler, D. M. Hofman, B. K. Meyer, T. Detchprohm, H. Amano, I. Akasaki, Jpn. J. Appl. Phys. **34,** L1178 (1995).
[21] J. Sun, K. A. Rickert, J. M. Redwing, A. B. Ellis, F. J. Himpel, T. F. Kuech, Appl. Phys. Lett. **76**, 415 (2000).
[22] J. S. Jang, T. Y. Seong, J. Appl. Phys. **88**, 3064 (2000).
[23] S. C. Binari, L. B. Rowland, W. Kruppa, G. Kelner, K. Doverspike, D. K. Gaskill, Electron. Lett. **30**, 1248 (1994).
[24] W. Jenkins, J. D. Dow, Phys. Rev. B **39**, 3317 (1989).
[25] B. P. Luther, S. E. Mohney, T. N. Jackson, Semicond. Sci. Technol. **13**, 1322 (1998).
[26] C. A. Dimitriadis, Th. Karakostas, S. Logothetidis, G. Kamarinos, J. Brini, G. Nouet, Solid-State Electron. **43**, 1969 (1999).