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Non-alloyed Cr/Au Ohmic contacts to N-face and Ga-face n-GaN

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ABSTRACT

Non-alloyed Cr/Au Ohmic contacts on N-face and Ga-face n-GaN were studied. The specific contact resistances (ρ_c) of Cr/Au contacts onto the N-face and Ga-face n-GaN were as low as $2.4 \times 10^{-4}\,\Omega\,cm^2$ and $2.4 \times 10^{-5}\,\Omega\,cm^2$, respectively. Native oxide formed on the n-GaN surface was believed to be the key factor for higher ρ_c. The results of X-ray photoelectron spectroscopy confirmed that n-GaN samples with different surface polarities or treated by different chemical solutions exhibited significant differences in gallium oxide content on the surface, which led to a marked difference in the ρ_c of non-alloyed Cr/Au Ohmic contacts to GaN films.

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1. Introduction

Recently, InGaN/GaN light-emitting diodes (LEDs) have been widely applied to traffic signs, backlighting of liquid crystal displays, and general lighting. White LEDs used as general lighting sources are operated at relatively high power compared with LEDs used in backlighting or traffic signs. At present, the efficiency of GaN LEDs is still not perfect. High-power operation means mass heat generation in LEDs. Therefore, thermal management becomes a critical point in high-power white LEDs. However, conventional GaN/sapphire-based LEDs may be not suitable for next-generation general lighting due to the poor thermal conductivity of the sapphire substrate. Vertical GaN-based LEDs, whose sapphire substrate was removed by laser lift-off (LLO) method and whose epitaxial layer was bonded to a good thermal and electrical conductive substrate such as Si and Cu, have demonstrated high-power operation characteristics [1–3]. Generally, III-nitride semiconductors grown by metal organic vapor-phase epitaxy on sapphire substrate with low-temperature-grown GaN or AlN buffer layers exhibit Ga-face surface polarity [4]. Therefore, for vertical LEDs, GaN surface with N-face polarity is created after the removal of the sapphire substrate using the LLO process. This means the n-type electrode contacts in the vertical GaN LEDs are formed on the N-face GaN surface. Metal contacts on Ga-face n-GaN surface have been widely studied in the past decade. Different metals, such as Ti/Al- and Cr/Au-based metals, have been proven to exhibit good Ohmic contact property and stability when deposited on the Ga-face n-GaN surface [5]. The Ti/Al-based contacts are the most popular metal schemes for n-GaN due to their low work function. However, they do not alleviate the need for high annealing temperatures to form intermetallic alloys further with low work function at the metal/semiconductor interface [5]. The effect of thermal annealing on the electrical property of metal contacts was different between the Ti/Al- and Cr/Au-based contacts on the Ga-face n-GaN surface [5]. Several reports have recently revealed that Al-based metal contacts could form low-resistivity Ohmic contacts on the N-face n-GaN surface [6,7]. However, there is still a dearth of studies on Cr/Au-based metals on the N-face n-GaN surface. As the chemical activity of N-face GaN surface was considered to be relatively higher than that of Ga-face GaN surface, the characteristics of metal contacts deposited on the Ga-face GaN surface would be substantially different from the contacts on the N-face n-GaN surface. In this study, we performed the non-alloyed Cr/Au-based Ohmic contacts on Ga-face and N-face GaN surfaces to elucidate the properties of both contact schemes.

2. Experiment

In this study, Si-doped n-type GaN(n-GaN) epitaxial films with carrier concentration of $1 \times 10^{19}/cm^3$ were grown by MOVPE on sapphire substrates. The surface

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of n-GaN epitaxial films exhibited Ga-face polarity (0 0 0 1). The growth procedure of the Ga-face n-GaN layers started with a low-temperature GaN nucleation layer deposited on the sapphire substrate. High-temperature unintentionally doped GaN (u-GaN) and Si-doped n-GaN were then sequentially grown. In contrast, n-GaN films with N-face polarity ($000\bar{1}$) were achieved using LLO and dry etching processes to remove the sapphire substrate and the u-GaN layer, respectively [1–3]. In this study, Indium (2.5 μm) and Ti/Pt/Au (30 nm/200 nm/100 nm) were deposited on the surface of GaN epitaxial wafer before the wafer bonding process. A silicon substrate deposited with Ti/Au (50 nm/600 nm) bilayer metals served as the template for the wafer bonding process. During the wafer bonding process, wafers were brought together under 8 kg/cm^2 pressure and an elevated temperature of 210 °C. A 248 nm excimer laser served as the light source to conduct the LLO process for removing the sapphire substrate from the bonded wafers. The n-GaN films were transferred to the Si substrates. To investigate the effect of surface treatment on the property of Ohmic contacts, bilayer metals of Cr/Au (50 nm/1.5 μm) were deposited on the Ga-face and N-face n-GaN films. Hydrochloric acid (HCl)-based solutions were used to treat the GaN surface before metal deposition onto the GaN films to form Ohmic or Schottky contacts because the native oxide layer inherently forms as the GaN films are exposed to the atmosphere [8,9]. In this study, two different HCl-based solutions were used to treat the N-face n-GaN films for 4 min before the deposition of Cr/Au metals: $HCl:H_2O = 1:2$ solution maintained at an elevated temperature of 50 °C and $HCl:H_2O = 1:10$ maintained at room temperature. Samples treated by the former solution were labeled sample A, whereas samples treated by the latter were labeled sample B. Ga-face n-GaN films treated by $HCl:H_2O = 1:10$ solution for 4 min were also prepared for comparison and were labeled sample C.

3. Results and discussion

Fig. 1 shows the typical *I–V* characteristics of the as-deposited Cr/Au contacts on samples A, B, and C. All samples exhibited Ohmic property. The specific contact resistances (ρ_c), which were determined by the transmission line model of the Cr/Au contacts on samples A, B, and C, were 2.4×10^{-4}, 2.4×10^{-5}, and 6.7×10^{-5} $\Omega\,cm^2$, respectively. For the formation of Ohmic contact to n-type semiconductors, two main mechanisms govern carrier transport across the metal/semiconductor interface, i.e., thermionic emission and tunneling. For Au/Cr/n-GaN contacts, tunneling is considered to be the primary mechanism for low-resistance Ohmic contact, especially for semiconductors with heavy doping. As Ga- and N-face n-GaN films have the same bulk carrier concentration, which is as high as $1 \times 10^{19}/cm^3$, carrier transport through the Cr/n–GaN interface is inevitably conducted through the tunneling mechanism [5]. The Ga- and N-face n-GaN films used in this study were degenerated semiconductors. Therefore, the non-alloyed Ohmic characteristics were expected and reasonable. However, the remarkable difference in ρ_c between the experimental samples implied that n-GaN films with different surface polarities or treated by different chemical solutions possessed a substantial difference in surface states between the GaN films.

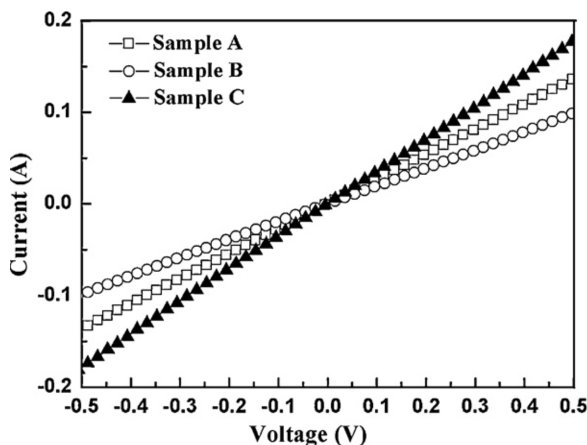

Fig. 1. Typical *I–V* characteristics of the as-deposited Cr/Au contacts on the n-GaN samples A, B, and C. The spacing between contact pads (100 μm × 100 μm) was 40 μm.

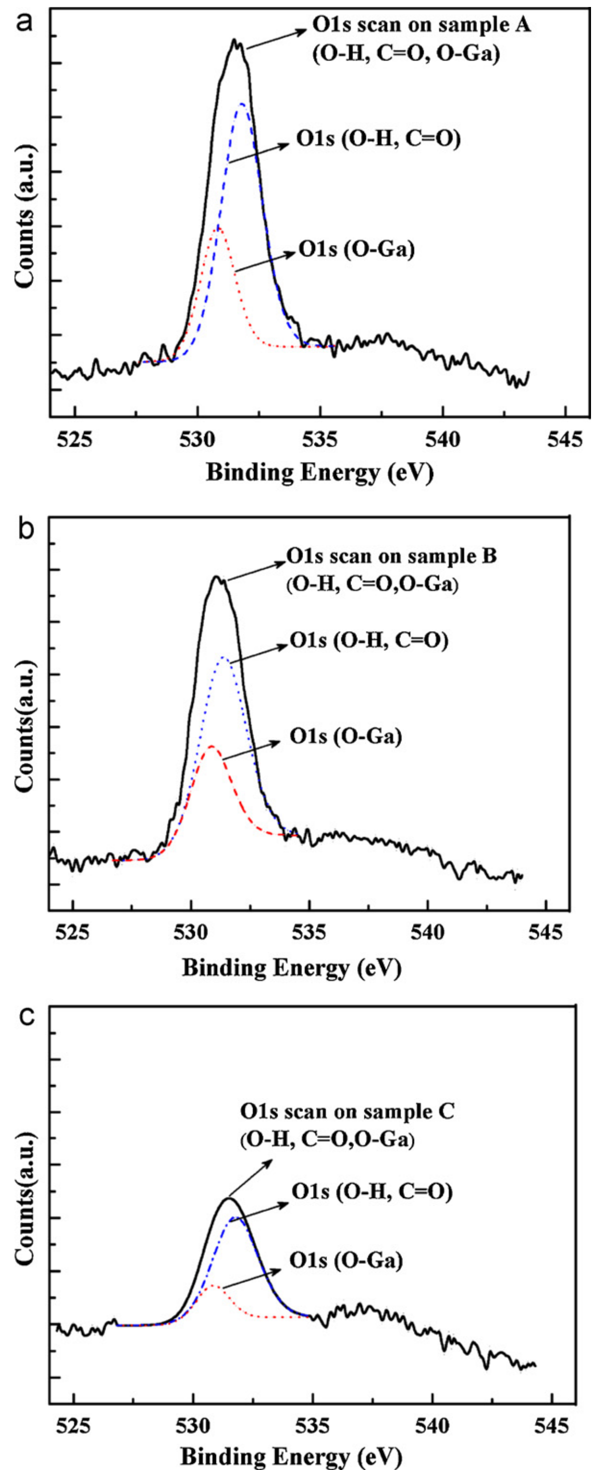

Fig. 2. Displays the XPS spectra of O 1s photoelectrons for (a) sample A (b) sample (c) sample C.

Karrer et al. proposed that surface band bending in Ga-face n-GaN is far larger than that in N-face n-GaN due to the higher spontaneous polarization in the Ga-face n-GaN layer [10]. Therefore, metal contacts on Ga-face n-GaN have higher Schottky barrier heights compared with those on the N-face n-GaN. In the light of the aforesaid contention, metal contacts on N-face n-GaN can generate lower Ohmic contact resistance compared with those on Ga-face n-GaN. In this study, the as-deposited samples C exhibited a markedly lower ρ_c compared with the as-deposited samples A

Table 1
The atomic contents of Ga, N, and O taken from the n-GaN samples A, B, and C by XPS.

Samples	Ga (at.%)	N (at.%)	O (at.%)	
			C=O + O—H	Ga—O
Sample A	40.6	39.9	16.4	3.1
Sample B	42.8	40.0	11.5	5.7
Sample C	51.8	40.2	6.3	1.7

and B. Ti/Al contacts on Ga-face n-GaN have demonstrated that AlN interface layers formed after thermal annealing can create polarization-induced two-dimensional electron gases (2DEG) at the AlN/GaN interface to facilitate carrier transport and reduce ρ_c [11]. However, significant interfacial alloy compounds, such as CrN, should be absent in the as-deposited Au/Cr/n-GaN samples. In addition, the band gap energy of CrN is lower than that of GaN [12]. Therefore, the lower ρ_c obtained from the as-deposited samples C is not attributed to the polarization-induced 2DEG at the Cr/GaN interface to facilitate carrier transport. Zywietz et al. reported that N-face GaN surface generally exhibits higher activity towards oxygen adsorption [13]. Considering the as-deposited samples B and C, the difference in ρ_c values is attributed to the easier formation of native gallium oxides on the N-face GaN surface compared with the Ga-face GaN surface. Fig. 1 shows that the as-deposited samples A have a lower ρ_c value compared with samples B. This result is due to the fact that native oxide can be removed further from the N-face GaN surface when the samples were treated in heated HCl solution. To clarify this point, X-ray photoelectron spectroscopy (XPS) was used to analyze the surfaces of the n-GaN samples. Fig. 2 displays the XPS spectra of O 1s photoelectrons for samples A, B, and C, respectively. To separate the chemical bonding states, the spectral line shape was simulated using a suitable combination of Gaussian functions. Fitting the O 1s spectra with 3 components, O—H, C=O, and Ga—O bonds, the integrated intensity of Ga—O peak in the Ga-face samples was markedly lower than those in the N-face samples. In contrast, the magnitude of Ga—O bonds obtained from samples A was lower than those from samples B. Table 1 shows the atomic contents of Ga, N, and O in samples A, B, and C. According to Table 1, there are two facts where samples C exhibited Ga-rich surface and had lower oxygen content originating from native oxide. These results are consistent with those in the previous reports stating that the N-face GaN surface has higher activity towards oxygen adsorption. The former fact induced higher surface carrier concentration due to the relatively higher nitrogen vacancies, namely, Ga-rich surface. The latter fact led to a lower potential barrier at the Cr/n–GaN interface. As a result, the Cr/Au contacts on the Ga-face n-GaN (samples C) exhibited lower contact resistance. Although the total oxygen content in samples A was higher than that in samples B, the component of Ga—O bonds in samples B was higher than that in samples A. Therefore, heated HCl solution is believed to remove native gallium oxide effectively from the N-face n-GaN surface. Evidently, native gallium oxide is the key factor influencing the contact property, not the C=O and/or O—H bond-containing compounds.

4. Conclusion

In summary, non-alloyed Cr/Au Ohmic contacts on Ga-face and N-face n-GaN were studied. Although the N-face GaN surface, which has lower band bending, was more beneficial to the formation of Schottky contacts with lower barrier heights than the contacts on Ga-face GaN, the property of higher activity towards oxygen adsorption on the N-face GaN surface was harmful to the formation of low-resistivity Ohmic contacts. It was confirmed that heated HCl solution could further remove the native gallium oxide from the N-face GaN surface, thereby reducing the specific contact resistance of non-alloyed Cr/Au contacts on the N-face GaN.

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