Nonalloyed Cr/Au-based Ohmic contacts to n-GaN

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Nonalloyed Cr/Au-based metal contacts to n-GaN have been demonstrated. The deposited Au/Cr/n-GaN contacts exhibited a specific contact resistance ($\rho_c$) of approximately $5.6 \times 10^{-3}$ $\Omega$ cm$^2$. Although the nonalloyed Ti/Al-based contacts to n-GaN can also exhibit a comparable $\rho_c$ value, their thermal stability is inferior to the Cr/Au-based contacts. This could be attributed to the fact that Al tends to ball up during thermal annealing. Thus, the surface morphology of most of the annealed Ti/Al-based contacts was quite rough, and the contacts became rectified when they were annealed at a temperature below 700 °C. However, the annealed Cr/Au-based contacts exhibited an Ohmic characteristic and had a smooth surface when annealing temperatures did not exceed 700 °C. In addition, the thermal stability could be further improved by inserting a Pt layer between the Cr and Au layers. This scheme could prevent the diffusion of Au into the Cr layer, thus preventing Au from reaching the Cr/GaN interface where it could form a possible Ga–Au phase, which would degrade the Ohmic contacts. © 2007 American Institute of Physics. [DOI: 10.1063/1.2803067]

Although the GaN-based devices have been commercialized, a few issues for high reliability in these devices are still attracting researchers to engage in investigation into these fields. One of the key requirements for these devices is low resistance. Reliable Ohmic contacts are capable of withstanding elevated temperatures and high current densities. 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. The former case occurs when the work function of metal is less than or close to semiconductors. For metal/ n-GaN contacts, tunneling is believed to be the primary mechanism for low resistance Ohmic contact, especially in the case of semiconductors with heavy doping. The Ti/Al-based contacts are the most popular metal schemes in n-GaN devices due to their low work function. However, they do not alleviate the need for high annealing temperatures to further form intermetallic alloys with low work function at the metal/semiconductor interface.\textsuperscript{1−4} However, the bilayer Ti/Al scheme is easily prone to converting to high resistance after thermal annealing at an intermediate temperature range. This could be due to the formation of an Al$_2$O$_3$ layer on the Al layer, leading to an increase in the contact resistance.\textsuperscript{2} Although the oxidation layer could be partially avoided by using Au as a passivation layer along with a diffusion barrier layer, such as Ni, Pt, and Ti disposed between Al and Au layers, the Ti/Al-based metallization systems went from Ohmic at as deposited to rectified when they were annealed at an intermediate temperature range. Papanicolau et al.\textsuperscript{5} suggested that this change is related to the formation of a TiN layer during the annealing process.\textsuperscript{3} This initial TiN phase possibly forms a heterojunction or a quasi-metal-insulator-semiconductor (MIS) structure, resulting in a higher barrier height, which causes a degradation of Ohmic contact, but the Ti/Al-based metallization systems could convert to Ohmic and exhibit a specific contact resistance ($\rho_{cv}$) as low as $10^{-3} \sim 10^{-5}$ $\Omega$ cm$^2$ when they are annealed at higher temperatures. However, annealing at high temperatures has been suspected of causing degradation in device performance and reliability because Al has a low melting point (~660 °C) and tends to ball up during thermal alloying. Thus, the surface morphology of most of the Ti/Al-based contacts was quite rough.\textsuperscript{4} In addition, relaxation of the III-nitride heterostructures during high-temperature annealing would also cause degradation in device performance.\textsuperscript{5} In this study, we examined the stability of Al-free metal schemes in n-GaN at different annealing temperatures. The Cr/Au and Cr/Pt/Au metallization systems used in this study could solve the high-temperature stability problems that result from the low melting point of Al and the high propensity of Al and Ti for oxidation. Detailed results will be subsequently discussed.

The Si-doped GaN epitaxial layers were 2.5 $\mu$m thick. Inductively coupled plasma (ICP) etching using Cl$_2$/Ar/H$_2$ gas was first performed on the n-GaN,\textsuperscript{6} and then a N$_2$-ambient thermal annealing at 600 °C for 5 min was sequentially performed on the etched n-GaN prior to metal deposition.\textsuperscript{18} Before Hall measurements were taken, samples of 5 $\times$ 5 mm$^2$ size were cut from the wafers, and metal (Ti/Al) dots of 0.1 $\times$ 0.1 mm$^2$ size were deposited to form electrodes in the four corners. The result revealed that the surface treated epitaxial layers had a bulk carrier concentration of around $1 \times 10^{18}$ cm$^{-3}$ and a mobility of approximately 350 cm$^2$/V s. The etching process could remove an oxide layer or leave the surface very heavy n type through preferential sputtering of nitrogen, i.e., creation of nitrogen vacancies. In addition, postetch annealing is believed to further convert the GaN surface into heavy n type through de-

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of approximately 2.6 \text{nm}.

To etch through the n-type GaN layer down to the sapphire substrate, a 400 nm thick Ni layer, serving as the etching mask, was patterned on the n-GaN layer using a photolithography technique. Prior to the deposition of the Ohmic metallization systems, the samples were cleaned in an HCl:H2O (1:10) solution for 3 min and then rinsed in deionized water to remove the native oxide on the n-GaN surface. Cr/Au (50/250 nm), labeled as sample B, and Cr/Pt/Au (50/20/250 nm), labeled as sample C, were prepared using an electron-beam evaporator. The TLM patterns were developed using a lift-off technique. In this study, Ti/Al/Ti/Au (20/50/20/250 nm) metallization on n-GaN, labeled as sample A, was also prepared for comparison.

To study the stability of the experimental samples, they were annealed in a N2 atmosphere at 400, 500, 600, 700, and 800 °C for 5 min. The current voltage (I-V) characteristics of the samples were measured using an HP4156C semiconductor parameter analyzer. Scanning electron microscopy (SEM) was used to evaluate the surface morphologies of the metal contacts on the GaN layer.

Figure 1(a) shows the typical I-V characteristics of samples A when annealed at different temperatures. Notably, all I-V characteristics shown in this article were measured from two adjacent metal pads with a spacing of 5 \text{nm}. One can see that the as-deposited sample A displays linear I-V characteristics that corresponds to a \( \rho_c \) of approximately 5.4 \times 10^{-5} \text{ } \Omega \text{cm}^2. Although the \( \rho_c \) value of the as-deposited contact is reasonably good, a moderate heat treatment is necessary to achieve a robust Ohmic contact. Unfortunately, after the thermal annealing process was performed at 400 °C on sample A, they display a rectifying behavior with very low current in the \pm 1 \text{V} bias range, as shown in Fig. 1(a). They remain rectified even after the 500 and 600 °C annealings. The as-deposited sample A showed that the linear I-V characteristic can be attributed to the fact that the carrier concentration of n-GaN is high enough to lead to an Ohmic contact via a tunneling mechanism. However, rectifying characteristics can be observed from the samples with annealing temperatures lower than or equal to 600 °C. Similar arguments have been reported that the rectifying characteristic could be attributed to the formation of the TiN layer between the Ti and GaN layers and the formation oxides of the Al and/or Ti layers, resulting in a higher barrier height, which causes a degradation of Ohmic contact. As shown in Fig. 1, when annealing temperatures are 700 and 800 °C, the I-V curves convert to similar results compared to that of the as-deposited characteristic (Ohmic behavior). The 700 °C annealed and 800 °C annealed samples exhibited \( \rho_c \) values of around 2.6 \times 10^{-4} and 4.2 \times 10^{-3} \text{ } \Omega \text{cm}^2, respectively, as shown in Table I. This could be due to the fact that Al could diffuse into the TiN layer, thus reaching the metal/semiconductor interface where it forms AlN or a stable Ti–Al–N phase with a more favorable work function for forming the Ohmic contact. Although the low resistance Ti/Al-based Ohmic contact could be achieved by the high-temperature annealing process, the high-temperature process has been suspected of causing degradation in device performance, as mentioned previously. To avoid this problem, we attempted to use Cr/Au-based schemes with high melting points. As shown in Fig. 1(b), the as-deposited sample B (Au/Cr/n-GaN) also show a linear I-V characteristic and have a \( \rho_c \) value of around 5.6 \times 10^{-5} \text{ } \Omega \text{cm}^2. Different from those of sample A, sample B showed the lowest \( \rho_c \) value of around 2.9 \times 10^{-5} \text{ } \Omega \text{cm}^2 when they were annealed at 400 °C, as shown in Table I. The \( \rho_c \) value of annealed sample B increased with an increase in annealing temperatures; even the electrical property changed from Ohmic to exhibit Schottky characteristics. This phenomenon could be attributed to the fact that the number of CrN islands that form between the Cr and GaN layers increase with an increase in annealing temperatures. The CrN islands possibly formed a localized heterojunction or quasi-MIS structure, resulting in a higher barrier height, which caused a degradation of the Ohmic contact.

**FIG. 1.** Current-voltage characteristics of different contacts deposited onto n-type GaN. These contacts were annealed at various temperatures in nitrogen ambience for 5 min. (a) Au/Ti/Al/Ti/n-GaN, (b) Au/Cr/n-GaN, and (c) Au/Pt/Co/n-GaN.
of Ohmic contact when annealing temperatures do not exceed 600 °C, as shown in Fig. 1(b) and Table I. Furthermore, they displayed a rectifying behavior with very low current in the ±1 V bias range when the samples were annealed at temperatures of 700 and 800 °C, which is different from that of sample A, as shown in Fig. 1(a). The possible reason could be that the AlN interlayers that occurred in high-temperature-annealed sample A (Ti/Al-based contacts) were absent in sample B because of the Al-free metal scheme in sample B. In contrast, Au could diffuse into the Cr layer, thus reaching the Cr/GaN interface where it forms an unstable Ga–Au phase, which deteriorates the adhesion of the metal contact on the GaN surface, thereby causing degradation in electrical characteristics in sample B that were annealed at temperatures of 700 and 800 °C. This contention could be indirectly clarified through the observation of the SEM images. Figure 2 shows the SEM images taken from sample B. One can see that the as-deposited sample showed a near featureless surface morphology. However, the surface became rougher as the annealing temperatures increased, especially in the cases of 700 and 800 °C annealed samples. This trend is consistent with the observed change in $\rho_s$ upon changes in the annealing temperature, as shown in Table I. As mentioned previously, the degradation of surface morphology could be due to the diffusion of Au into the Cr layer, which thereby reaches the Cr/GaN interface to form the Ga–Au phase. Although the electrical properties of the Cr/Au contacts are better than those of Ti/Al/Ti/Au contacts, the pursuit of a more stable contact is still necessary, especially for applications in devices that operate under high-power and/or high-temperature conditions. To solve the problems of Au diffusion at high temperatures, which degrade the performance of Cr/Au/n-GaN contacts, we used a Pt layer that was inserted between Cr and Au to serve as a diffusion barrier. As shown in Fig. 1(c), all I-V curves are linear except that of an 800 °C annealed sample, which means an Ohmic contact was achieved. This suggests that the Pt insertion layer should indeed play the role of diffusion barrier. Therefore, sample C could endure the annealing temperatures up to 700 °C and still maintain the Ohmic characteristic. In addition, from SEM images (not shown here), a marked difference was not observed in the surface morphology among all the annealed sample C except for that of 800 °C annealed sample C. Based on the contention that the degradation of annealed Cr/Au-based contacts is due to the diffusion of Au and its sequential reaction with GaN, this finding is consistent with the observed change in $\rho_s$ values as the annealing temperatures changed, as shown in Table I and Fig. 2.

In summary, we have demonstrated nonalloyed Cr/Au and Cr/Pt/Au Ohmic contacts to n-GaN, which exhibit the specific contact resistances of approximately $5.6 \times 10^{-5}$ and $6.5 \times 10^{-5}$ $\Omega \text{cm}^2$, respectively. These values were comparable with that of the Ti/Al/Ti/Au contacts. However, the Cr/Au-based contacts exhibited a superior thermal stability as compared to those of Ti/Al/Ti/Au contacts when a moderate temperature was utilized for these samples. In particular, the Cr/Au-based contacts could endure a higher annealing temperature and maintain the Ohmic characteristic when a Pt layer was inserted between the Cr and Au layer. We believe that the Pt insertion layer played the role of diffusion barrier to prevent the formation of the Ga–Au phase at the Cr/GaN interface.

| TABLE I. Specific contact resistance ($\rho_s$) of Ti/Al/Ti/Au, Cr/Au, and Cr/Pt/Au contacts to n-GaN. The unit of these $\rho_s$ values is $\Omega \text{cm}^2$. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                | As deposited    | 400 °C          | 500 °C          | 600 °C          | 700 °C          | 800 °C          |
| Ti/Al/Ti/Au                   | $5.4 \times 10^{-5}$ | Non-Ohmic       | Non-Ohmic       | Non-Ohmic       | $2.6 \times 10^{-4}$ | $4.2 \times 10^{-5}$ |
| Cr/Au                        | $5.6 \times 10^{-5}$ | $2.9 \times 10^{-5}$ | $9.0 \times 10^{-5}$ | $2.0 \times 10^{-3}$ | Non-Ohmic       | Non-Ohmic       |
| Cr/Pt/Au                      | $6.5 \times 10^{-5}$ | $1.4 \times 10^{-4}$ | $1.3 \times 10^{-4}$ | $5.4 \times 10^{-4}$ | $2.8 \times 10^{-3}$ | Non-Ohmic       |

FIG. 2. SEM images taken from the Au/Cr/n-GaN samples annealed at various temperatures. (a) as deposited, (b) 400 °C, (c) 500 °C, (d) 600 °C, (e) 700 °C, and (f) 800 °C.