Interfacial reaction and surface morphology of Pd/Re contact schemes to p-type GaN

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The interfacial reactions between the Pd (20 nm) / Re (25 nm) contacts and p-GaN (1.13×10^{17} \text{cm}^{-3}) have been investigated using glancing angle XRD and Auger depth profiling. The samples are annealed at temperatures of 550 °C and 650 °C for 1 min in a nitrogen ambient. The I-V measurements show that the as-deposited sample is ohmic with a contact resistance of 1.4×10^{-3} \Omega \text{cm}^2. However, the annealing of the sample at 550 °C results in much better ohmic behaviour with a specific contact resistance of 8.7×10^{-4} \Omega \text{cm}^2. Further, increase in annealing temperature (650 °C) causes the degradation of the ohmic property. Based on AES and XRD results, the formation of Ga-Pd reaction phases results in the generation of Ga vacancies at the GaN surface region, which plays a role in reducing contact resistivity. The AFM results show that the surface morphology of the as-deposited contact is fairly smooth (with a rms roughness of 1.7 nm) and when annealed at 550 °C, contact has become somewhat degraded with a root-mean-square roughness of 6.5 nm.

[Keywords: interfacial reaction, Pd/Re contacts, surface morphology, glancing angle XRD, Auger depth profiling]
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1 Introduction

Group III nitride semiconductors, especially GaN, have recently attracted much attention for opto-electronic devices such as light emitting diodes and laser diodes in blue and ultraviolet wavelength ranges \(^1\text{-}^4\). One of the major obstacles in developing high-performance GaN-based devices is achieving thermal stability, low-resistance ohmic contacts to p-type GaN. Recently, efforts have been made to obtain reliable ohmic contacts to p-type GaN using Ni- and Pt-based metallization schemes. Research on interfacial reactions and the formation of ohmic contacts with metals are of interest with respect to device applications.

Several groups \(^5\text{-}^{10}\) have attempted to understand interfacial reactions and microstructures of metals and GaN e.g., Ni, Ni/Au, Ni/Pt/Au, Pt and Pd. However, slightly different types of interfacial products have been reported, although the reactions were studied in a roughly similar range of temperatures. For example, Sheu \textit{et al.}\(^7\) have studied interfacial reactions between Ni/Au and GaN. It was shown that compound phases such as Ga_{3}Ni_{2}, Ga_{4}Ni_{3} and Ni_{3}N (or Ni_{4}N) were found in the temperature range of 500-700 °C, similar to those as in the as-deposited sample.

Jang \textit{et al.}\(^8\) investigated the interfacial reactions of Ni/Pt/Au contact schemes to p-GaN. It was shown that Ga- (Pt, Ni) phases such as Ga_{3}Pt_{5} and Ga_{4}Ni_{3} were formed at temperature 500 °C, while in addition to Ga_{3}Ni_{2}, new phases of GaAu_{2} and GaAu were formed upon annealing at temperatures \(\geq 600\) °C. Kim \textit{et al.}\(^10\) investigated structural evolution of the Pd films on GaN (0001) using powder X-ray diffraction (θ-2θ scan) and revealed the existence of interfacial, epitaxial, Pd grains in the as-deposited sample. It was also shown that annealing at 700 °C lead to the formation of two kinds of epitaxial Pd gallides. In this paper, we investigated the interfacial reactions of Pd/Re contact schemes to p-GaN before and after annealing using glancing angle X-ray diffraction and Auger electron microscopy. Also the electrical property of the contact scheme is presented. A possible explanation is given to describe why the contact schemes degrade as the temperature increases.

2 Experimental Details

Metalorganic chemical-vapour deposition was used to grow a 2 μm-thick undoped GaN layer on c-plane sapphire substrate, on which a 1.5 μm-thick p-
type GaN : Mg layer was grown. The carrier concentration was determined to be $1.13 \times 10^{17} \text{cm}^{-3}$ by means of Hall effect measurements with the Van der Pauw geometry. The 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 boiling aqua regia [$\text{HNO}_3 : \text{HCl } (1:3)$] for 10 min followed by a deionized water rinse and a dry nitrogen blow. The circular transmission line method (CTLM) pads were patterned on $p$-type GaN layer by a standard photolithography technique. The inner dot radius was 25 $\mu$m and the spacing between the inner and the outer radii were varied from 3 to 18 $\mu$m. Prior to metal deposition, the CTLM-patterned layers were dipped in BOE solution for 30 sec. A Pd/Re (20 nm/25 nm) film was then deposited on the surface treated $p$-type GaN by electron beam evaporation under a pressure of $1 \times 10^{-6}$ torr. Some of the samples were annealed at temperatures of 550 and 650 °C for 1 min under nitrogen ambient in a rapid thermal annealing system. Current and voltage characteristics $(I-V)$ of the contacts were measured using a semiconductor parameter analyzer. Auger electron microscopy (AES) depth profiling was employed to characterize the extent of interdiffusion between metal layers and the GaN before and after annealing.

The interfacial reaction products formed were identified by glancing angle X-ray diffraction (GXRD) (using Cu $\alpha$ radiation). Atomic force microscopy (AFM) was used to characterize the surface morphology of the samples.

3 Results and Discussion

3.1 Current-voltage $(I-V)$ characteristics

The typical $I-V$ characteristics of Pd/Re contact scheme to $p$-GaN are shown in Fig. 1. The as-deposited contact exhibits near-linear behaviour, which is further improved when annealed at 550 °C. The specific contact resistance $(\rho_c)$ was measured (by the c-TLM method $^{11}$) to be $1.4 \times 10^{-3} \Omega \text{cm}^2$ for the as-deposited sample and $8.7 \times 10^{-4} \Omega \text{cm}^2$ for the sample annealed at 550 °C. This improvement may be related to the presence of Ga-Pd phases formed during annealing. The result shows that the optimum temperature for the Pd/Re scheme is 550 °C. However, the $I-V$ characteristic is largely degraded upon annealing at 650 °C. The degradation at 650 °C seems to be associated with the deterioration of the interfacial contacts due to the breaking up of the contact schemes.

3.2 Interfacial reactions

Fig. 2(a) shows the AES depth profile of the as-deposited Pd/Re contact. It is shown that the
individual layers of Pd and Re are well defined, indicating the absence of significant interfacial reactions between the metal layers and the GaN. Glancing angle XRD examination was also made with as-deposited sample to characterize interfacial reactions products, Fig 2(b). The XRD plot shows the characteristic diffraction peaks of Pd (111) and Re (100), (101), (110), (103). There is no evidence of interfacial reactions between the metals and the GaN.

Fig. 3 (a) shows the AES depth profile of the sample annealed at 550 °C. For the 550 °C contact, some amount of Ga out-diffused into the Pd layer, was compared with the as-deposited sample. The out-diffused Ga reacted with Pd to form Ga-Pd phases. In addition, a small amount of nitrogen was also out-diffused into the Pd layer. However, no nitride phase was detected by XRD [Fig. 3(b)]. It is also shown that Pd diffused towards the sample surface through the Re layer. Figure 3(b) shows the glancing angle XRD plot of the sample annealed at 550 °C. In addition to the phases, which were observed in the as-deposited sample, there are new diffraction peaks, being indicative of the formation of new interfacial phases. The reaction phases are identified as Ga$_2$Pd$_5$ (181),
(400) and Ga$_3$Re (206). The occurrence of these additional peaks seems to be consistent with outdiffusion of Ga into the Pd layer.

The AES depth profile of the samples annealed at 650 °C is shown in Fig. 4(a). The profiles illustrate that the extent of the GaN dissociation is greater at 650 °C than that at 550 °C and also Ga and N out-diffused into the metal layers. The XRD plot of the sample annealed at 650 °C is shown in Fig 4(b). In addition to the Ga$_3$Pd$_5$ (181), (400) and Ga$_3$Re (206) peaks, there is a new extra peak, which is identified to be Ga$_5$Pd (213), as expected from the AES results [Fig. 4(a)]. It is noteworthy that the Re layer remain very stable even after annealing at 650 °C.

In the present work, the $I$-$V$ characteristic of the as-deposited Pd/Re contact was improved when the scheme was annealed at 550 °C. It is worth noting that reaction products such as Ga$_3$Pd$_5$, Ga$_3$Re and Ga$_5$Pd are formed upon annealing at temperatures in the range of 550 °C and 650 °C. Thus, comparison of the results obtained from the as-deposited and 550 °C samples indicates that the improvement in the $I$-$V$ behaviour is due to the formation of the Ga-Pd phases. The formation of Ga-Pd reaction phases results in the generation of Ga vacancies, acting as acceptors for electrons at the GaN surface region, which results in reducing contact resistivity. Another possible factor is related to the contact area. The interfacial reactions would lead to a rough interface, resulting in an increase in the contact area. Therefore, improved specific contact resistance for 550 °C contacts can be related to the combined effects of the increases in the carrier concentration and contact area. However, further increase in the annealing temperature led to the rectifying behaviour, as shown in Fig. 1. This degradation could be related to either the disruption of the interface [Fig. 4], a reduction in the contact area or both.

3.3 Surface morphology

The surface morphology of the ohmic contacts is critical since the alloying treatment normally required to form the contacts usually involves solid-state reactions at the metal/semiconductor interface, which results in surface roughness that adversely affects the uniformity and reproducibility. The surface morphologies of the Pd/Re contacts were assessed by atomic force microscopy (AFM). Fig. 5 shows AFM images of the as-deposited and annealed Pd/Re contacts on the $p$-GaN. It was shown that the surface of the as-deposited sample was fairly smooth with a root-mean-square (rms) roughness of 1.7 nm, Fig. 5(a). However, the surface of the annealed at 550 °C sample became somewhat degraded with a rms roughness of 6.5 nm, Fig. 5(b). The degraded surface may be associated with the out-diffusion of Pd through the Re layer, as shown by the AES results [Fig. 3 (a)]. The surface of the sample, which was annealed at 650 °C, was rough with an rms roughness of 8.7 nm, Fig. 5(c). This was attributed to a “balling-up” effect, which has been widely observed in metallization processes, which would lead to a decrease in the contact area and hence cause an increase in the contact resistance.
Conclusions

Pd (20 nm)/Re (25 nm) layers on the p-GaN (p = 1.13×10^{17} \text{cm}^{-3}), which were annealed at temperature of 550 ºC and 650 ºC for 1 min in a nitrogen ambient, were investigated using I-V measurement, glancing angle XRD and AES. The contact produced a specific contact resistance of 8.7×10^{-4} \Omega \text{cm}^2 when annealed at 550 ºC. It was shown that the formation of reaction products was annealing temperature-dependent. It was also shown that Ga-Pd interfacial phases such as Ga_{3}Pd_{5} and Ga_{3}Re, formed upon annealing at 550 ºC, could be responsible for the significant improvement in the electrical property of the contacts. The AFM results showed that the surface roughness of the as-deposited contact was fairly smooth with a rms roughness of 1.7 nm. However, surface roughness of the sample annealed at 650 ºC became degraded with a rms roughness of 8.7 nm (and hence a reduction in the contact area) resulting in rectifying behaviour.

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References