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The Effect of Heat Treatment on Ni/Au Ohmic Contacts to p-Type GaN

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The effect of heat treatment temperature on the microstructure and specific contact resistance of oxidized Ni(5 nm)/Au(5 nm) contacts to p-type GaN was investigated. The minimum specific contact resistance (ϱ_c) obtained was 4×10^{-6} Ω cm^2 after heat treating at 500 °C in air for 10 min. The cross-sectional microstructure of heat treated Ni/Au films on p-type GaN was examined with transmission electron microscope (TEM) in conjunction with compositional analyses. The high value of ϱ_c for samples heat treated at lower temperatures (< 400 °C) was attributed to the fact that Au islands and crystalline NiO detached from the p-type GaN. When the temperature increased to 500 °C, NiO films and Au islands epitaxially constructed on p-type GaN matrix. The crystalline NiO may play a crucial role in the formation of low-resistance ohmic contact to p-GaN. Increasing the temperature further to 600 °C, large voids adjacent to p-GaN were observed which resulted in the reduction of contacting area deteriorating the contact resistance.

1. Introduction

Gallium nitride, a direct wide-band gap semiconductor, is attractive for optoelectronic devices such as blue and green light emitting diodes (LEDs) and blue laser diodes (LDs). Demanding of low-resistance ohmic contacts to both n- and p-type GaN to fabricate reliable LDs is urgent. In contrast to the well developed ohmic contacts to n-type GaN [1, 2], low-resistance ohmic contacts to p-type GaN were lacking. The values of specific contact resistance to p-GaN were reported between 10^{-2} to 10^{-4} Ω cm^2 [3 to 5]. Recently, Ho et al. [6, 7] successfully developed a novel contact to p-type GaN with $\varrho_c = 4 \times 10^{-6}$ Ω cm^2 using an oxidized Ni(5 nm)/Au(5 nm) contact. In order to understand the mechanism for this remarkable result, the effect of heat treatment temperatures on the microstructure and specific contact resistance of oxidized Ni/Au contacts have been studied.

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2. Experiment

The Mg-doped/GaN (2 μm) with undoped GaN (2 μm) samples deposited on sapphire were prepared by metal-organic chemical vapor deposition. The Mg-doped p-type GaN layers had hole concentrations of 2×10^{17} cm^{-3} after annealing in N_2. Prior to metal deposition, the samples were etched with $HCl:H_2O = 1:1$, and then 5 nm Ni and 5 nm Au were subsequently deposited on the p-type GaN by electron beam evaporation. The as-deposited Ni/Au samples were then heat treated in air for 10 min. The specific contact resistance was characterized by current–voltage (I–V) measurements based on the circular transmission line model (CTLM). The contact pattern for CTLM measurements had a constant inner radius $r = 150$ μm and spacings of 14, 17, 20, 26, 32, 40, 50, and 70 μm, respectively. Microstructural and compositional analyses were performed using a JEOL 2010F field-emission-TEM equipped with an Oxford energy dispersive X-ray spectrometer (EDS). During the crystal structure identification and EDS analysis, the electron beam diameter was focused to 0.5 nm.

3. Results and Discussion

The cross-sectional TEM examination indicated that the as-deposited Ni and Au layers were grown with the preferred orientation $(002)_{Au}//(002)_{Ni}//(0002)_{GaN}$. No interlayer was observed between Ni and p-type GaN, which implied no contamination on p-GaN surface during deposition [8]. The I–V measurement displayed that the as-deposited Ni/Au contacts exhibited rectifying characteristics. However, the oxidation heat treatment dramatically converted the Ni/Au contacts from Schottky-type to ohmic. ϱ_c of Ni/Au contacts heat treated at various temperatures is shown in Fig. 1. The minimum value $4 \times 10^{-6}\ \Omega\,cm^2$ was obtained at 500 °C. At 350 °C, ϱ_c was high ($1.2 \times 10^{-2}\ \Omega\,cm^2$). With further increasing of temperature to 600 °C, the value of ϱ_c was increased to $3.2 \times 10^{-3}\ \Omega\,cm^2$. These results suggested that there are optimum heat treatment temperatures for obtaining lowest value of ϱ_c.

In order to understand the phase transformation related to the formation of low-resistance ohmic contact, cross-sectional TEM examination was performed to investigate the microstructure of the Ni/Au contact heat treated at various temperatures in air. Fig. 2a, b and c represent the typical cross-sectional microstructures of the Ni/Au contacts heat

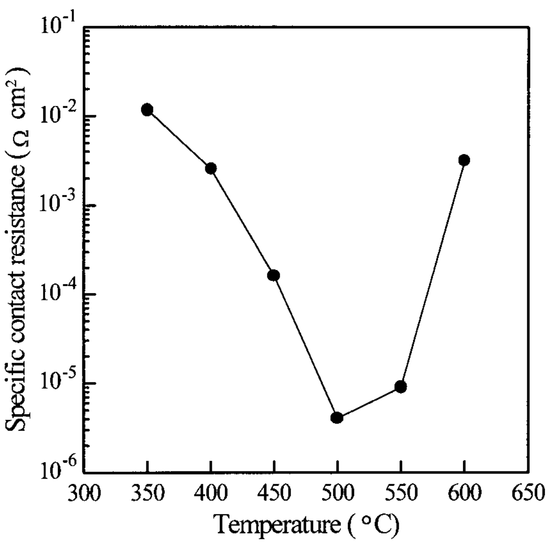

Fig. 1. The effect of heat treatment temperature on the specific contact resistance of Ni(5 nm)/Au(5 nm) contact to p-GaN heat treated in air for 10 min

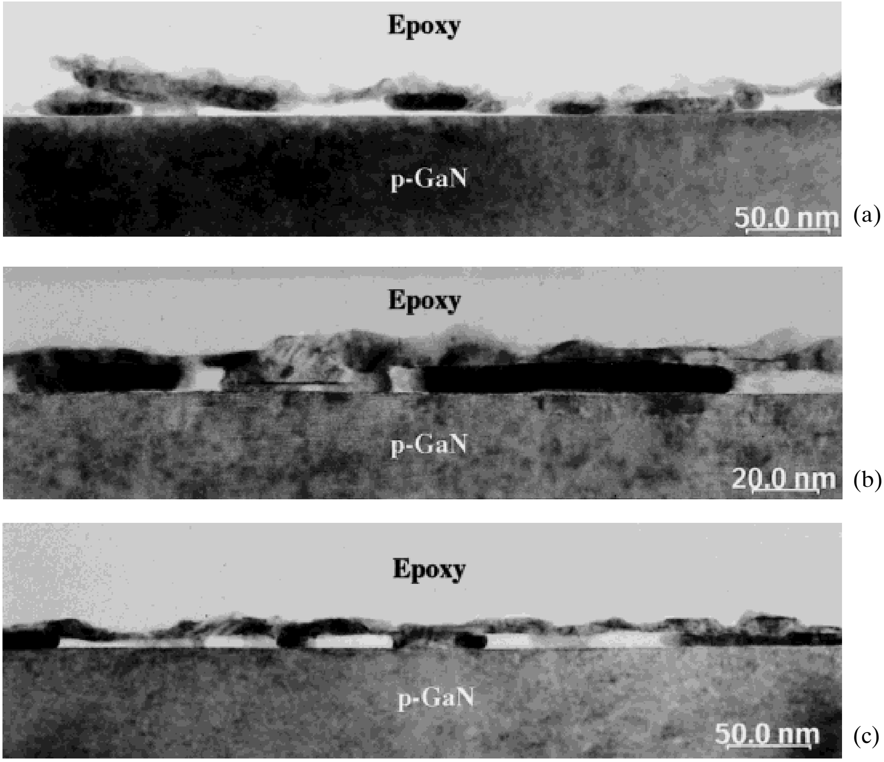

Fig. 2. Cross-sectional microstructure of the Ni(5 nm)/Au(5 nm) contacts to p-type GaN heat treated at a) 350, b) 500, and c) 600 °C, for 10 min in air

treated in air at 350, 500, and 600 °C, respectively. The Ni/Au bi-layer film heat treated at 350 °C transformed to a new microstructure with discrete crystalline islands of darker contrast and a non-uniform crystalline thin film covering the islands. The nanobeam diffraction patterns identified the discrete islands as Au grains, and the crystalline film above the Au islands was NiO. Also, there existed an amorphous layer between some of these features and p-type GaN. Although the heat treatment at 350 °C is enough to change Ni/Au contact to ohmic, many Au islands still did not connect to p-type GaN due to the slow diffusion of Au atoms at such low temperature, the special contact resistance is still high. In addition, most of the crystalline NiO also did not directly contact to p-type GaN.

Heat treating the samples at 500 °C in air, the NiO film and the Au islands epitaxially constructed on p-type GaN epi-layer. The orientation relationship was determined as $(111)_{NiO} \parallel (11\bar{1})_{Au} \parallel (0002)_{GaN}$ and $[1\bar{1}0]_{NiO} \parallel [1\bar{1}0]_{Au} \parallel [11\bar{2}0]_{GaN}$. Besides, an amorphous phase and small voids were found among Au islands. The EDS analysis showed that some of the Au islands contained small amount of Ni, but the percentage was less than 5%. The amorphous phase consisted of a relatively larger amount of Ga as well as Ni and O. Accordingly, three new interfaces were observed, Au/GaN, NiO/GaN and amorphous Ga–Ni–O/GaN. Comparing to the results at 300 °C, it indicates that the amorphous Ga–Ni–O phase does not effectively contribute to reduction of ϱ_c, and also

Au alone is unable to obtain low ϱ_c [9]. Therefore, the crystalline NiO film is considered to be crucial to obtain the low ϱ_c value. NiO was found to behave as a p-type semiconductor with Ni^{2+} vacancies and/or interstitial O [10]. The low specific contact

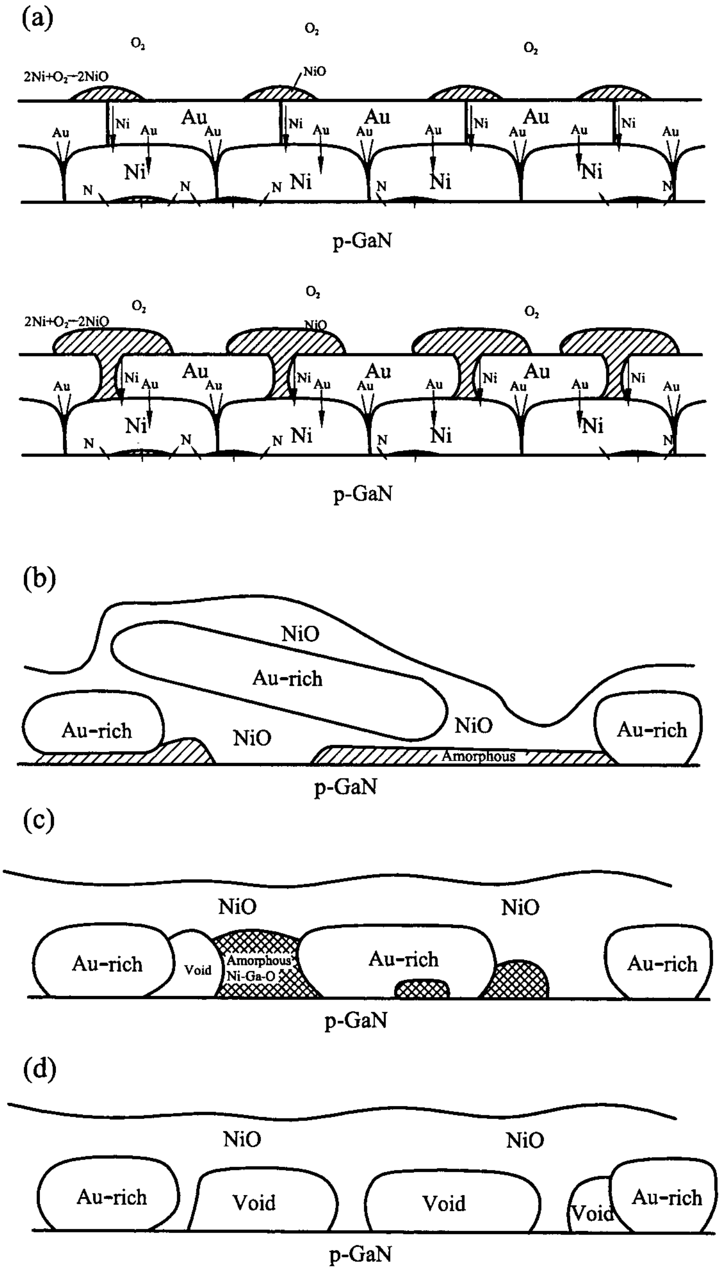

Fig. 3. a) The initial diffusion and oxidized reaction of the oxidizing heat treatment; the microstructure of oxidized Ni/Au contact heat treated at b) 350, c) 500, and d) 600 °C

resistance was attributed to the high conductivity of Au islands and low contact barrier of p-NiO to p-GaN.

The microstructure of the Ni/Au contact heat treated at 600 °C was similar to that heat treated at 500 °C, as shown in Fig. 2c. However, ϱ_c increased to $3.2 \times 10^{-3}\ \Omega\,cm^2$ at temperature higher than 500 °C. The major difference of the microstructure between the Ni/Au contacts heat treated at 600 and 500 °C was the size and amount of voids. The disassociated nitrogen from interfacial reactions may create many voids, which can deteriorate the contact resistance [8]. At higher temperatures, the interfacial reaction may release more N_2 to enlarge the voids. These voids separate the crystalline NiO from p-type GaN and reduce the contacting area. The diminishing of effective contacting area may increase the value of ϱ_c. From the above results, the proposed structural transformation of Ni/Au metallization heat treated at 350, 500 and 600 °C were depicted in Fig. 3.

4. Conclusion

The effect of heat treatment temperatures on the microstructure and specific contact resistance of oxidized Ni/Au contact to p-type GaN was investigated. The heat treatment converts the Ni/Au bi-layer film to a new microstructure of a mixture of crystalline NiO, Au, and an amorphous phase. This transformation changed the Ni/Au contact from rectifying characteristic to ohmic. The crystalline NiO may play an important role for obtaining the low-resistance ohmic contact to p-GaN. In this study, the optimum heat treatment temperature is about 500 °C where ϱ_c as low as $4 \times 10^{-6}\ \Omega\,cm^2$ can be attained.

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