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High-transparency Ni/Au ohmic contact to *p*-type GaN

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In this study, a very thin Ni/Au bilayer metal film was prepared by electron beam evaporation and thermal alloying to form ohmic contact on *p*-type GaN film. After thermal alloying, the current–voltage ($I-V$) characteristic of Ni/Au contact on *p*-type GaN film exhibited ohmic behavior. The Ni/Au contacts showed a specific contact resistance of $1.7\times10^{-2}\ \Omega\ \mathrm{cm}^2$ at an alloying temperature of 450 °C. In addition, the light transmittance of the Ni/Au (2 nm/6 nm) bilayer on *p*-type GaN was measured to be around 85% at 470 nm. These results suggest that a suitable metallization technology for the fabrication of light emitting devices can be achieved. © *1999 American Institute of Physics.* [S0003-6951(99)00816-5]

GaN based semiconductors have recently been applied to fabricate optoelectronic devices such as light emitting diodes (LEDs) and laser diodes (LDs) in the blue and violet light region.[1–3] They also have the potential for fabricating electronic devices operating at high temperatures up to 300 °C due to their superior physical properties, such as wider band gap, high breakdown field, and high thermal conductivity.[4,5] In order to improve the performance of LEDs with reduced contact resistance, reliable ohmic contacts on both *n*- and *p*-type GaN films are required. An improved ohmic contact with Ti/Al deposited on *n*-type GaN layer with a carrier concentration of $\sim1\times10^{17}\ \mathrm{cm}^{-3}$ has been demonstrated by Lin *et al.*[6] The specific contact resistance was as low as $8\times10^{-6}\ \mathrm{cm}^{-2}$ after the sample was annealed at 900 °C for 30 s by rapid thermal annealing (RTA). Several studies about ohmic contact on *n*-type GaN films deposited with other metals have been reported.[7,8] In contrast to the many studies of ohmic contact on *n*-type GaN, very few detailed investigations of ohmic contact on *p*-type GaN were reported.[9,10] In a GaN based LED, Ni/Au are commonly used as ohmic contact on *p*-type GaN top layer.[1–3] However, the low doping level of the *p*-type GaN layer may result in a non-ohmic contact, thereby degrading the performance of devices. In addition, the current coming from the top electrode cannot be spread effectively through the entire chip due to the high resistivity of the *p*-type GaN. One way to avoid this so-called current crowding problem, thereby obtaining high efficiency and uniform light emission from the device, is to design the pattern of the top electrode to be interdigitated finger shape. However, this type of electrode reduces the emitted light output. Thus, a low resistive *p* electrode with high transparency is an important issue for fabrication of GaN-based LED, although the well known transparent conducting films such as indium tin oxide (ITO) and cadmium tin oxide (CTO) have been used as the electrode of light emitting diodes.[11,12] However, in our study, ITO transparent conducting film on *n*-GaN (with carrier concentration of $3\times10^{17}\ \mathrm{cm}^{-3}$)[13] and *p*-GaN (with carrier concentration of $3\times10^{17}\ \mathrm{cm}^{-3}$) showed Schottky contact characteristics after thermal annealing. If the carrier concentration of GaN increases to the order of larger than $1\times10^{18}\ \mathrm{cm}^{-3}$, the formation of ITO ohmic contact on GaN may be possible. However, the hole concentration of *p*-GaN is hardly higher than $1\times10^{18}\ \mathrm{cm}^{-3}$. In this study, we used a thin Ni/Au ohmic contact on *p*-type GaN film. We have demonstrated that both low contact resistance and high light transmittance can be achieved at the same time.

The Mg-doped GaN was grown on a *c*-face sapphire substrate by metalorganic vapor phase epitaxy (MOVPE). Trimethylgallium (TMGa) and ammonia (NH_3) were used as the sources for Ga and N, respectively; hydrogen was used as a carrier gas. Before growing the thicker high-temperature GaN epitaxial layer, a low-temperature nucleation layer nominally 30 nm thick was deposited at 525 °C. The high-temperature Mg-doped GaN epitaxial layer was grown at 1050 °C at a growth rate of 3 μm/h. CP_2Mg was employed as the *p*-type dopant. The as-grown Mg-doped GaN film was semi-insulating with a resistivity greater than $10^6\ \Omega$ cm. In order to obtain *p*-type GaN film, thermal annealing was performed at 750 °C to activate the dopant. The ambient gas was N_2 and the annealing time was 30 min. The hole concentration of the *p*-type GaN film was determined by Hall measurements at room temperature. For the Hall effect measurement, a sample of $5\times5\ \mathrm{mm}^2$ size was cut from the wafer and metal (Ni/Au) dots were evaporated in the four corners to obtain electrical contacts in the Van der Pauw geometry. The Hall effect measurement showed that the film was *p* type with a hole concentration of $3\times10^{17}\ \mathrm{cm}^{-3}$ and a mobility of 12 cm^2/V s. Prior to metal deposition, the *p*-type GaN sample was cleaned by HCl:H_2O(1:1) solution, and followed by deionized (DI) water rinsing. The metals were then deposited onto the *p*-GaN by thermal evaporator at a chamber pressure of $\sim1\times10^{-6}$ Torr. In this study, Ni/Au contact was formed

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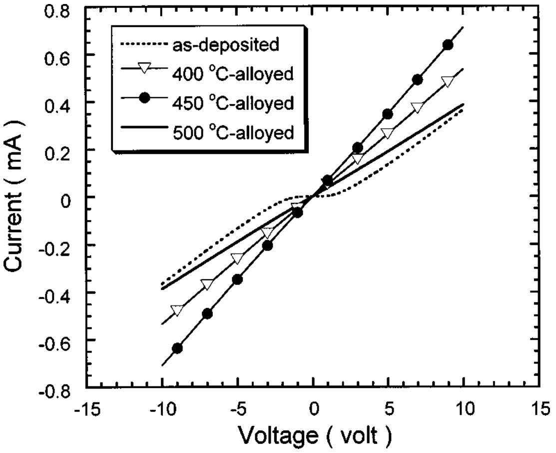

FIG. 1. The $I-V$ curves of Ni/Au contacts on *p*-type GaN films alloyed at various temperatures.

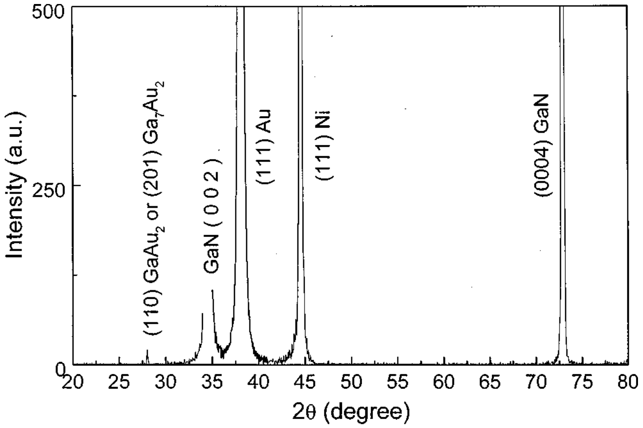

FIG. 2. The XRD spectrum of 450 °C alloyed Ni/Au contacts on *p*-type GaN layers.

on *p*-GaN with 2 nm of Ni and 6 nm of Au, respectively. Specific contact resistance was evaluated by using a circular transmission line model (TLM). The circular TLM pattern was formed by standard photolithographic techniques. After the formation of the TLM pattern, thermal alloying with temperature ranging from 400 to 500 °C and temperature interval of 50 °C in N_2 ambient were performed on the Ni/Au metal contacts. The current–voltage ($I-V$) characteristics were measured at room temperature using an HP4145B semiconductor parameter analyzer. The light-transmission characteristics of Ni/Au contact were measured by a Hitachi U3000 photospectrometer.

Figure 1 shows the $I-V$ characteristics of Ni/Au dot contacts on *p*-type GaN films. The diameter and the interspacing of dot contacts were 130 and 170 μm, respectively. The samples were alloyed at temperatures ranging from 400 to 500 °C. Only the as-deposited sample exhibited a nonlinear $I-V$ characteristic. The 450 °C alloyed sample exhibited the best $I-V$ characteristic among all samples. The improvement of $I-V$ characteristics may be attributed to the interfacial reactions taking place between Ni, Au, and GaN and their alloys extending into GaN film. However, as the alloying temperature increases to 500 °C, the $I-V$ characteristics became worse and unstable. This could be attributed to poor adhesion of the metallic contact on GaN film due to the fully depletion of Ni, thereby resulting in the interfacial roughening. On the other hand, as the thermal alloying was performed to the Ni/Au (2 nm/6 nm) contact on *p*-GaN, Au readily diffuses through Ni into the metal/GaN interface which reacts with GaN to form the Au–Ga intermetallic phase and then mixing with the Ga–Ni intermetallic phase at the vicinity of the interface. Considering these possible interfacial reactions, it may be the cause of achieving the improved $I-V$ characteristics of Ni/Au contact on *p*-type GaN. However, if the thickness of the Ni of the Ni/Au bilayer is increased to 25 nm, the $I-V$ characteristics could be improved by increasing the alloying temperature up to 700 °C.[14] In our study, the outdiffusion of Ni was clearly observed by Auger electron spectroscopy (AES) depth profiles as the thermal alloying was performed to the Ni/Au contact on *p*-GaN. Ni and Au also diffused into the GaN film and reacted with the GaN film at the vicinity of the interfacial to form interfacial compounds, such as Ga_4Ni_3, Ga_3Ni_2, GaAu, and $GaAu_2$.[14] To identify the possible reactions, the measurements of x-ray diffraction (XRD) in a grazing incident angle configuration had been performed. Figure 2 shows the XRD spectra of alloyed Ni/Au contacts on *p*-type GaN. After 450 °C alloying, in addition to the peaks of (0002) GaN, (0004) GaN, (111) Ni, and (111) Au, an extra peak at around $2\theta = 28.4$ were also detected, as shown Fig. 2. Note that this small peak at around $2\theta = 28.4$ may be identified to be (110) $GaAu_2$ or (201) Ga_7Au_2. It indicates that the Au–Ga intermetallic phase was formed at the vicinity of the interface after thermal alloying. Other intermetallic phases should also exist at the vicinity of metal/semiconductor interface but these reaction phases might be too thin to be detected in our present XRD system. Some further studies, such as the analysis of high resolution transmission electron microscopy and high resolution and high power x-ray diffraction in grazing incident angle configuration, will be conducted to understand the interfacial reaction. These interfacial chemical products can substantially influence the electrical properties of the contacts. As illustrated in Fig. 1, linear $I-V$ curves were obtained after thermal alloying. This may be attributed to the formation of Ga–Ni and/or Ga–Au compounds at the metal/semiconductor interface and then mixing, thereby reducing the barrier height. Although, Foresi and Moustakas[15] observed that metal contacts on GaN should have barrier heights which depend directly on the difference of the work function between the metal and GaN. However, as generally known, chemical reactions between the metal and the semiconductor can substantially influence the electrical properties of metal-semiconductor contact. In a practical metal/semiconductor system with Fermi level pinning, the Schottky barrier height is empirically expressed as $f_{bn} = Sf_m + C$, where S is a slope parameter and C is a constant. In other words, the formation of the interfacial compounds near the metal/GaN interface during thermal alloying can possibly lead to a decrease of the S parameter, thereby influencing the barrier height.

In this study, the circular TLM was used to measure the specific contact resistance. Circular pattern design avoids the need for isolation of the contact structures by ion implantation or mesa etching.[16] Table I shows the specific contact resistance and light transmittance of Ni/Au contacts on

TABLE I. Specific contact resistance and transmittance (at 470 nm) of the Ni/Au contacts on *p*-type GaN films as function of alloying temperature.

	Transmittance	Specific contact resistance
400 °C, 5 min	60%	$2.35\times10^{-2}\ \Omega\ \mathrm{cm}^2$
450 °C, 5 min	83%	$1.70\times10^{-2}\ \Omega\ \mathrm{cm}^2$
500 °C, 5 min	88%	$2.43\times10^{-2}\ \Omega\ \mathrm{cm}^2$

p-type GaN films as a function of alloying temperature. The light transmittance for samples alloying at 450 and 500 °C are 83% and 88%, respectively. Note that the typical thickness of Ni and Au are 2 and 6 nm, respectively. For the 450 °C alloyed sample, the lowest value of specific contact resistance was found to be $1.7\times10^{-2}\ \Omega\ \mathrm{cm}^2$. As mentioned previously, the contact resistance of Ni/Au bilayer on *p*-type GaN films became larger as the alloying temperature is above 500 °C. It is well known that the specific contact resistance will be reduced if the thickness of the Ni/Au bilayer and the carrier concentration of *p*-GaN are increased. However, the increase of the Ni/Au bilayer will reduce the light transmission. Thus, there is a tradeoff between the value of contact resistance and the light transmittance. Figure 3 shows the measured light-transmission spectra of as-deposited, 400, 450, and 500 °C alloyed Ni/Au contacts on *p*-type GaN film. In our experiments, the *p*-type GaN films were grown on double polished sapphire substrates. These high-transparency *p*-GaN wafers were used as the references to calibrate the light-transmission measurements. As shown in Fig. 3, the light transmission increases as alloying temperature is increased. This is presumably due to the gradual decrease in Ni thickness with increasing alloying temperature. The thickness reduction is believed to be a consequence of Ni diffusion and its reaction with GaN at the metal/semiconductor interface, as mentioned above. Also, the Au was found to participate in the interfacial reaction with GaN near the metal–semiconductor interface.[14] As shown in Table I, the value of transmittance for Ni/Au contacts are 60%, 83%, and 88% (at 470 nm) for samples of 400, 450, and 500 °C alloyed, respectively. In general, to achieve good electrical property of Ni/Au contact on *p*-GaN, an optimum alloying temperature window, depending on the thickness of Ni/Au, needs to be chosen.

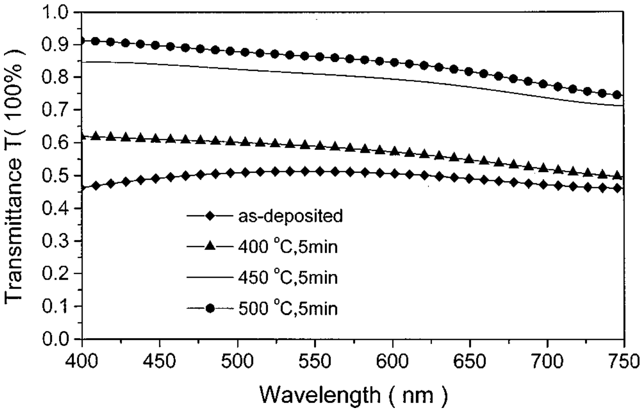

FIG. 3. The transmission spectra of as-deposited, 400, 450, and 500 °C alloyed Ni/Au contacts on *p*-type GaN films.

In conclusion, after thermal alloying, the $I-V$ characteristic of very thin Ni/Au contacts on *p*-type GaN films was demonstrated to be ohmic. For alloying temperature of 450 °C, the Ni/Au contacts to *p*-type GaN showed a specific contact resistance of $1.7\times10^{-2}\ \Omega\ \mathrm{cm}^2$. In addition, the light-transmission characteristics of the Ni/Au (2 nm/6 nm) bilayer on *p*-type GaN was measured. It clearly indicated that the transmittance of Ni/Au contacts increase with increasing alloying temperature. The optimum light-transmitting ohmic contacts alloyed at 450 °C typically exhibit a transmittance of 83%. GaN based light emitting diodes with low operation voltage and high efficiency can be successfully fabricated.

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