Low-resistance and thermally stable ohmic contact on *p*-type GaN using Pd/Ni metallization

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We report a low-resistance thermally stable ohmic contact on *p*-type GaN using a promising contact scheme of Pd/Ni. Specific contact resistance as low as $5.7\times10^{-5}\ \Omega\ \mathrm{cm}^2$ was obtained from the Pd (30 Å)/Ni (70 Å) contact annealed at 500 °C under an oxidizing ambient. NiO that formed at the surface prevented Pd atoms from outdiffusing, promoting the formation of Pd gallides, Ga_2Pd_5 and Ga_5Pd. This reaction produces Ga vacancies below the contact, leading to enhancement of the thermal stability as well as reduction of the contact resistivity. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1403660]

In developing GaN-related devices, low-resistance and thermally stable ohmic contacts are essential. For *n*-type GaN, ohmic contacts using Ti/Al-based metallization provide low contact resistivities ($<10^{-5}\ \Omega\ \mathrm{cm}^2$) and long-term thermal stability.[1–3] For *p*-type GaN, it is difficult to obtain contact resistivity lower than $10^{-4}\ \Omega\ \mathrm{cm}^2$ because of the difficulty in activating Mg dopants in *p*-type GaN and the absence of suitable metals with work functions higher than 6.5 eV.[4] Thus, a number of ohmic contacts have been reported, such as Ni/Au, Ni/Pd/Au, Pd/Au, Pd/Pt/Au, Pt/Ni/Au, and Ti/Pt/Au, using a Au overlayer.[5–8]

Of the above ohmic contacts, Ni/Au and Pd/Au contacts have been used as a transparent ohmic contact on *p*-type GaN because of their low contact resistivity. In Ni-based contacts, Ni is easily oxidized to form NiO above about 400 °C in an oxidizing ambient.[5] The NiO layer formed at the surface could act as a diffusion barrier like SiO_2. In Pd-based contacts, phase transformation from Pd to Pd gallides, forming ohmic contacts on *p*-type GaN, was observed after annealing at 700 °C.[9] Therefore, it is expected that a low-resistance and thermally stable transparent ohmic contact could be achieved using Pd/Ni metallization on *p*-type GaN.

In this letter, we report a promising contact scheme for Pd/Ni on *p*-type GaN. The optimum layer thickness ratio of Pd to Ni was chosen by evaluating contact resistivities as a function of the annealing temperature. The microstructure at the interface of metal contact with *p*-type GaN was analyzed by high-resolution x-ray diffraction (XRD) using synchrotron radiation. Depth profiles of elements were obtained from secondary ion mass spectroscopy (SIMS) measurements.

The GaN films used in this work were grown on (0001) sapphire substrates using metalorganic chemical vapor deposition (MOCVD). An undoped GaN buffer layer with a thickness of 1 μm was grown, followed by growth of 1-μm-thick *p*-type GaN doped with Mg. The samples grown were annealed at 750 °C by rapid thermal annealing (RTA) under N_2 atmosphere to generate holes. The net hole concentration was determined to be $3.3\times10^{17}\ \mathrm{cm}^{-3}$ by Hall measurements. For measurement of the specific contact resistivity using the transmission line method (TLM), an active region was defined by inductively coupled plasma, followed by dipping the samples into boiling aqua regia solution of $HCl:HNO_3(3:1)$ to remove surface oxides[7] formed during MOCVD and/or RTA. The TLM test structure was patterned onto the surface-treated samples. Two types of contacts were prepared. One was the deposition of Pd and Ni metals with various thicknesses in sequence by electron beam evaporation under pressure of 4×10^{-7} Torr. The other was the deposition of Pd (50 Å) and Au (50 Å) metals for comparison. After removing the metals deposited on the photoresist, the remaining metals with TLM patterns were annealed for 1 min in temperatures ranging from 300 to 600 °C by RTA under air atmosphere. For evaluation of both contacts, the samples were annealed at 550 °C up to 24 h. Current–voltage ($I-V$) characteristics of the contacts were examined by the four-point probe technique.

Figure 1(a) shows $I-V$ curves of Pd/Ni contacts with various thicknesses and the Pd/Au contact annealed at 500 °C for 1 min, measured between TLM pads with interspacings of 10 μm. The $I-V$ curve of the Pd (50 Å)/Au (50 Å) contact is nearly linear, but that of the Pd (50 Å)/Ni (50 Å) contact is linear. The contact resistance (R_c) in units of Ω/mm and the sheet resistance (R_s) in units of Ω/□ were determined from the intercept of the *y* axis and a slope of resistance of 0 V with the interspacings of the TLM pads. The specific contact resistivity (ρ_c) was calculated as $\rho_c = R_c^2/R_s$. The contact resistivities of the contacts were plotted as a function of the annealing temperature, as shown in Fig. 2(b). The minimum contact resistivities of the contacts are summarized in Table I. Contacts with a Pd/Ni thickness ratio lower than unity exhibited lower contact resistivities than those with a ratio higher than unity. The lowest value of $5.7\times10^{-5}\ \Omega\ \mathrm{cm}^2$ was obtained for the Pd (30 Å)/Ni (70 Å) contact. An order of magnitude improvement in contact resistivity is observed in the Pd/Ni contact relative to in the Pd/Au contact ($6.4\times10^{-4}\ \Omega\ \mathrm{cm}^2$). This value is the lowest among transparent ohmic contacts reported for *p*-type GaN.

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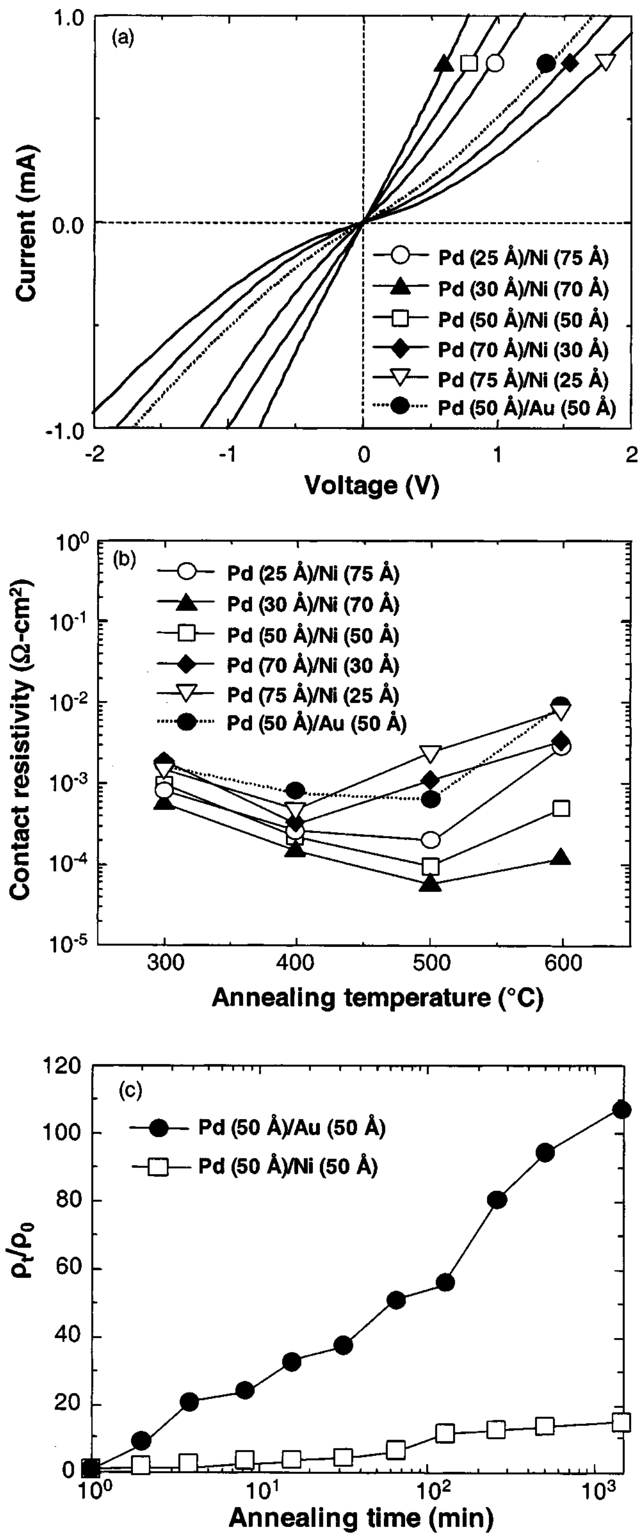

FIG. 1. (a) $I-V$ curve of the Pd/Ni and Pd/Au contacts annealed at 550 °C. Various thicknesses of Pd/Ni contacts were selected so that the total thickness might equal to 100 Å. (b) Contact resistivity of Pd/Ni and Pd/Au contacts as a function of the annealing temperature. (c) Change of the ratios, ρ_t/ρ_0, for both the Pd (50 Å)/Ni (50 Å) and Pd (50 Å)/Au (50 Å) contacts as a function of the annealing time at 550 °C.

Figure 1(c) shows the change in contact resistivity for both the Pd/Ni and Pd/Au contacts as a function of the annealing time at 550 °C. The contact resistivities were normalized to that in the annealed sample for 1 min, ρ_0, and plotted as ρ_t/ρ_0. The value of ρ_t/ρ_0 increased by a factor of 108 for the Pd/Au contact after annealing for 24 h, but it increased only by a factor of 16 for the Pd/Ni contact. The smaller increase in the ratio means the superior thermal stability of the Pd/Ni contact.

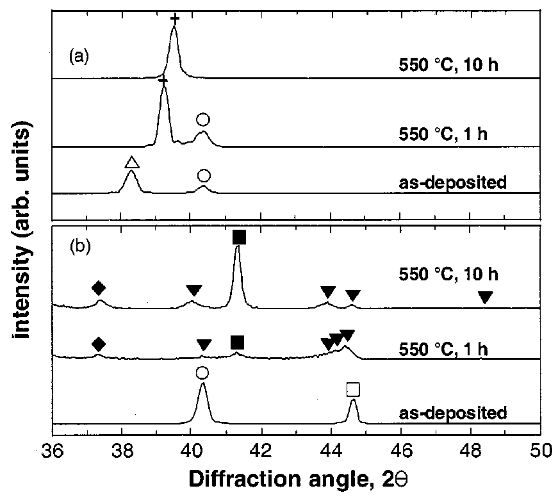

FIG. 2. XRD profiles as a function of the annealing time at 550 °C: (a) the Pd/Au contact and (b) the Pd/Ni contacts [□: Ni (111), ○: Pd (111), △ : Au (111), ■: Ga_5Pd, ▼: Ga_2Pd_5, ◆: NiO, +: Au–Pd solid solution].

Figure 2 displays XRD profiles of both Pd/Au and Pd/Ni contacts as a function of the annealing time at 550 °C. For the as-deposited condition, the XRD profiles of both contacts show that all metal layers were deposited along the (111) direction, which is the preferred orientation on a (0001) GaN epilayer. The epitaxial property of Pd layers in both contacts was observed using x-ray rocking curve analysis. In the Pd/Au contact, the Au peak shifted toward the higher angle and its intensity increased after annealing at 550 °C for 1 h, whereas the Pd peak showed no change in its peak position. This means that Pd outdiffusion occurred mainly rather than Au indiffusion during annealing, thus forming a Au–Pd solid solution. The increase in peak intensity in both the Au and the Pd peaks could be due to strain relaxation because only one peak along the (111) direction was found. After annealing for 24 h, Pd (111) and Au (111) peaks merged into one peak as shown in Fig. 2(a). This represents the formation of complete solid solution between Au and Pd. The XRD profiles of the Pd/Ni contact, shown in Fig. 2(b), were quite different from the Pd/Au one. Two metal peaks disappeared and new phases, NiO, Ga_2Pd_5, and Ga_5Pd, appeared after annealing. As the annealing time was increased, the peak intensity of all phases increased, especially in the epitaxial Ga_5Pd gallide. This suggests that Pd atoms indiffused into the GaN epilayer. By the results in Figs. 2(a) and 2(b), it is seen that the NiO layer suppressed the outdiffusion of Pd and

TABLE I. Minimum contact resistivities in Pd/Ni contacts with various thicknesses.

Sample	Annealing temperature (°C)	Contact resistivity (Ω cm^2)
Pd (25 Å)/Ni (75 Å)	500	1.5×10^{-4}
Pd (30 Å)/Ni (70 Å)	500	5.7×10^{-5}
Pd (50 Å)/Ni (50 Å)	500	9.6×10^{-5}
Pd (70 Å)/Ni (30 Å)	400	3.2×10^{-4}
Pd (75 Å)/Ni (25 Å)	400	4.8×10^{-4}
Pd (50 Å)/Au (50 Å)	500	6.4×10^{-4}

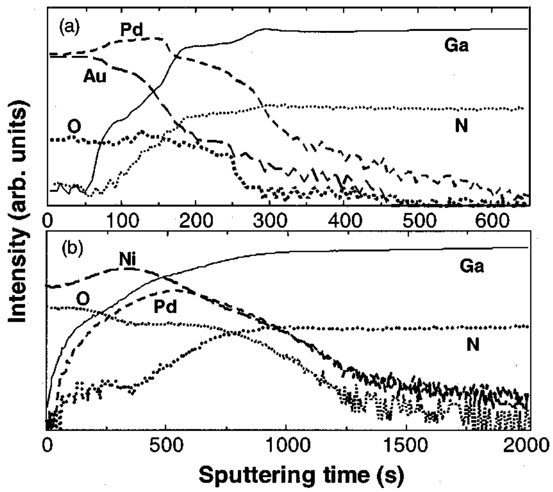

FIG. 3. SIMS depth profiles of (a) the Pd/Au contact and (b) the Pd/Ni contact annealed at 550 °C for 10 min.

played a crucial role in producing Pd gallides in the Pd/Ni contact.

SIMS depth analysis was carried out to study interfacial reactions during annealing, as shown in Fig. 3. The depth profile of the annealed Pd/Au contact shows that Pd has outdiffused through the Au layer and reached the surface, as shown in Fig. 3(a). The predominant outdiffusion of Pd in the annealed Pd/Au contact is comparable to the result of XRD analysis, resulting in the formation of complete Au–Pd solid solution. In comparing the Ga profile with the N one, Ga outdiffusion toward the surface is observed. This is due to Ga dissolution into the Au–Pd solid solution, which provides relatively easy outdiffusion of N atoms to the surface.[10] In the annealed Pd/Ni contact, the oxygen concentration at the surface was remarkably high and its depth profile was similar to the Ni one. This is the evidence of the NiO formation from Ni. The NiO prevented Pd atoms from outdiffusing to the surface. As a result, Pd gallides such as Ga_5Pd and Ga_2Pd_5 formed between the NiO and GaN substrates. Note that the Ga atoms outdiffused more in the Pd/Ni contact than in the Pd/Au contact.

Based on our experimental observations, the ohmic contact formation and good thermal stability in the Pd/Ni contact on *p*-type GaN can be explained. The NiO layer formed at the surface acted as a diffusion barrier of Pd. This accelerated Pd to react with GaN, leading to the formation of Pd gallides. As a result, Ga vacancies, acting as acceptors for electrons, were produced below the contact, and played a role in reducing contact resistivity. During the long-time annealing, Pd gallides were continuously produced, causing the contact to retain its thermal stability because of the generation of Ga vacancies. In addition, the NiO layer could suppress the outdiffusion of N atoms released from the decomposed GaN, and this led to the interfacial region being N rich, namely, degenerated GaN below the contact. Therefore good thermal stability and low contact resistivity could be obtained simultaneously.

In conclusion, specific contact resistivity as low as $5.7 \times 10^{-5}\ \Omega\ \mathrm{cm}^2$ was obtained using Pd (30 Å)/Ni (70 Å) on *p*-type GaN, which is lower by an order of magnitude relative to Pd/Au. The NiO layer formed at the surface promoted the reaction of Pd atoms with GaN to form the Pd gallides, resulting in achievement of the low contact resistivity. Pd gallides were continuously produced and NiO acted as a diffusion barrier for N outdiffusion, resulting in enhancement of the thermal stability.

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