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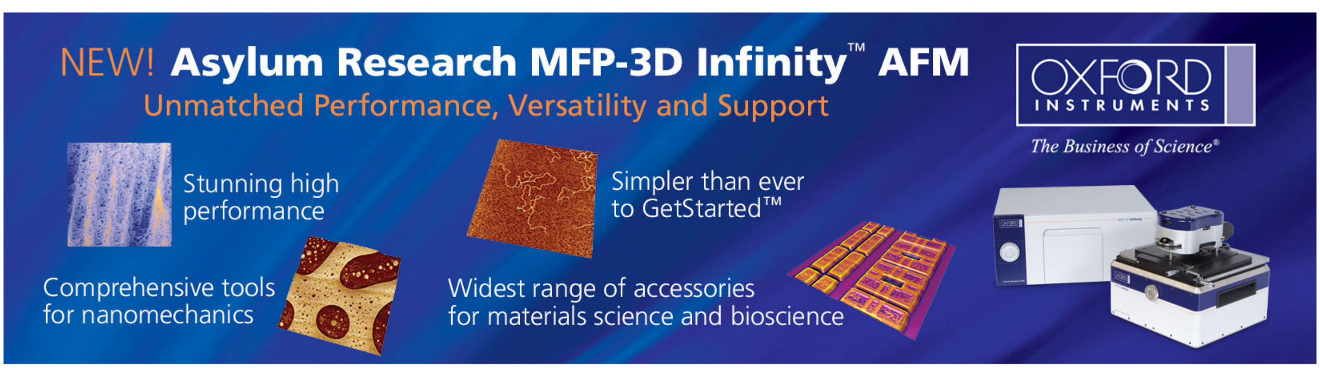

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Low-resistance ohmic contacts on *p*-type GaN using Ni/Pd/Au metallization

Chen-Fu Chu, C. C. Yu, Y. K. Wang, J. Y. Tsai, F. I. Lai, and S. C. Wang[a]
Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan, Republic of China

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In this letter, a low-resistance ohmic contact on *p*-type GaN using an alloy of Ni/Pd/Au is reported. The Mg doped *p*-type GaN samples were grown by metalorganic chemical vapor deposition with a carrier concentration of $4.1\times10^{17}\,\mathrm{cm}^{-3}$. The as-grown Mg doped samples were deposited with Ni (20 nm)/Pd (20 nm)/Au (100 nm) and then annealed in air, nitrogen, and oxygen ambient conditions at different annealing temperatures ranging from 350 to 650 °C. Linear $I-V$ ohmic characteristics were observed with specific resistance as low as $1.0\times10^{-4}\,\Omega\,\mathrm{cm}^2$ for the samples annealed in oxygen atmosphere. Similar contact metal composition was also deposited on Be-implanted *p*-type GaN samples with a carrier density of $8.1\times10^{19}\,\mathrm{cm}^{-3}$. Without further annealing process, the samples show good ohmic contact with a lowest specific resistance of $4.5\times10^{-6}\,\Omega\,\mathrm{cm}^2$. © *2000 American Institute of Physics.* [S0003-6951(00)01847-7]

GaN based semiconductors have been applied to fabricate optoelectronic devices such as light emitting devices, metal–semiconductor field effect transistors, ultraviolet photoconductive detectors, and diode lasers.[1–5] One of the serious concerns in particular for light emitting devices is the large voltage drop across the GaN/metal interface for ohmic contacts, which leads to poor devices performance.

For *n*-type GaN, ohmic contact with relatively low contact resistance of $10^{-5}-10^{-8}\,\Omega\,\mathrm{cm}^2$ using alloy composition such as Ti/Au, Ti/Al, and Ti/Al/Ni/Au,[6–8] have been achieved. However, for *p*-type GaN because of the difficulty in achieving high carrier density and the absence of suitable metals with high work function, a high-quality ohmic contact with low resistance is still relatively difficult to obtain. Many attempts have been reported thus far in finding ways of lowering the contact resistance in *p*-type GaN materials. Recently, various Au-based ohmic contacts using metallization such as Ni/Au,[9–11] Co/Au,[12] Pd/Au,[13] Pd/Pt/Au,[14] Ni/Pt/Au,[15] Pt/Ni/Au,[16] and Ti/Pt/Au[17] have been reported. These contact metallizations were either annealed in a nitrogen and oxygen environment or without any annealing. The specific contact resistance (ρ_c) was typically in the range of 2.1×10^{-2} to $4.2\times10^{-5}\,\Omega\,\mathrm{cm}^2$. The reduction of contact resistance for the Au-based ohmic contacts annealed in N_2 and O_2 atmosphere was attributed to either the removal of hydrogen atoms bounded to Mg or N atoms, or formation of an intermediate semiconductor layer such as *p*-NiO with high hole concentration. In this letter, we report a new contact metallization scheme using Ni/Pd/Au on *p*-type GaN in achieving linear current–voltage ($I-V$) characteristic with low ohmic contact resistance.

The Mg-doped *p*-type GaN samples were grown on sapphire substrate by the metalorganic chemical vapor deposition (MOCVD) system (Emcore D75). A 1 μm thick *p*-type epilayer was grown on the 1 μm thick undoped GaN. The carrier concentration of the as-grown *p*-type GaN measured by Hall measurement was about $4.1\times10^{17}\,\mathrm{cm}^{-3}$. Both circular and annular pads were patterned on the *p*-type GaN epilayer by the standard photolithography technique for measurement of specific contact resistance using circular transmission line method (CTLM). The inner dot radius was 200 μm and the spacing between the inner and the outer radii were varied from 3 to 45 μm. A metal contact layer structure of Ni (20 nm)/Pd (20 nm)/Au (100 nm) was deposited in sequence on the *p*-type GaN by electron beam evaporation under a pressure of 2×10^{-6} Torr.

Samples of *p*-type GaN with metallization were then annealed in different ambient conditions including air, nitrogen, and oxygen. The annealing temperature varies from 350 °C to 650 °C for 5 min to optimize the annealing conditions. Figure 1(a) shows the $I-V$ characteristics for the samples annealed in air at different annealing temperatures. A near ohmic characteristic is obtained as the annealing temperature rises to 450–550 °C. As the annealing temperature increases beyond 550 °C, the $I-V$ curve becomes nonlinear again. Figure 1(b) shows $I-V$ curves for samples annealed in a N_2 atmosphere that have similar temperature dependence as those annealed in air. Figure 2 shows the $I-V$ curves of the samples annealed in O_2 atmosphere. The $I-V$ curves for annealing temperature below 550 °C show good linear ohmic behavior with low resistance characteristics. Total resistance against the pad distance measurement by CTLM for the samples annealed at 550 °C under different ambient conditions was plotted in Fig. 3. The specific contact resistance determined from the intercepts and slopes in the plots has a value of 1.1×10^{-2}, 1.5×10^{-3}, and $1.0\times10^{-4}\,\Omega\,\mathrm{cm}^2$ for the sample annealed in air, N_2, and O_2, respectively. The results show that the samples annealed at 550 °C in oxygen have the best ohmic characteristic with a lowest specific resistance of $1.0\times10^{-4}\,\Omega\,\mathrm{cm}^2$.

The same Ni/Pd/Au contact metals were also used to deposit on the Be-implanted *p*-type GaN samples. These samples were prepared by implantation of Be ions with energy of 50 keV at a dose of $10^{14}\,\mathrm{cm}^{-2}$ on to the MOCVD as-grown Mg-doped *p*-type GaN materials first. Subse-

[a]Author to whom all correspondence should be addressed; electronic mail: scwang@cc.nctu.edu.tw

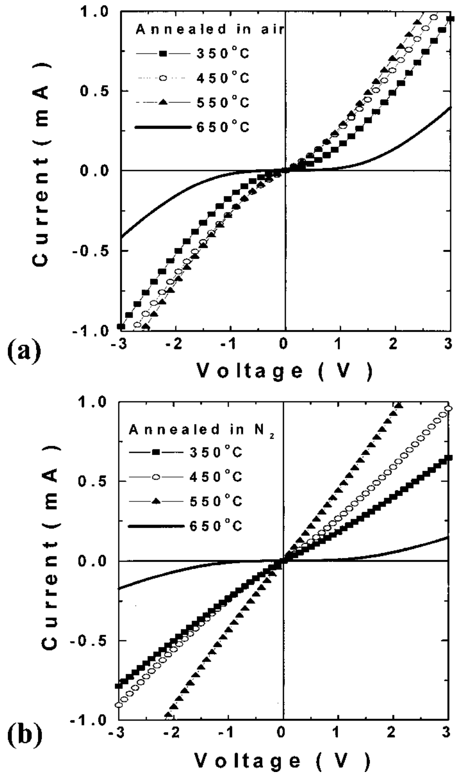

FIG. 1. Current–voltage (I–V) characteristics of Ni/Pd/Au contacts annealed in (a) air and (b) nitrogen for different annealing temperatures.

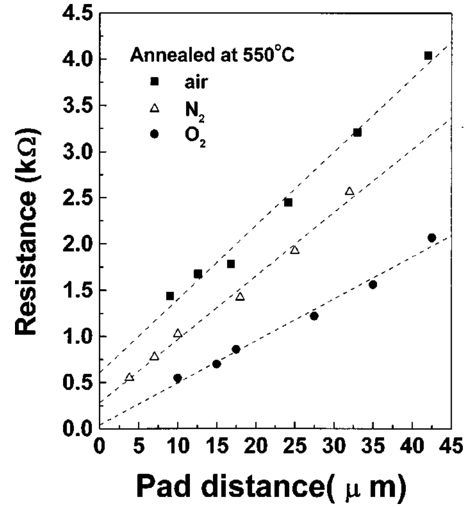

FIG. 3. Plot of the measured total resistance against the contact pad spacing for Ni/Pd/Au contacts annealed at 550 °C under different ambient conditions.

quently, the implanted samples were rapidly thermal annealed at 1100 °C for 60 s to repair the material damages induced by the implantation process. The annealed Be-implanted p-type samples show relatively higher carrier concentrations of $2.6\times10^{18}\,\mathrm{cm}^{-3}$–$8.1\times10^{19}\,\mathrm{cm}^{-3}$ than the as-grown p-type samples as measured by Hall measurement. Without any further annealing process after the contact metallization, these samples show near perfect linear I–V characteristic as depicted in Fig. 4. Total resistance measured by CTLM is shown in Fig. 5. The specific contact resistance determined from the intercepts and slopes in the plots has a very low value of $4.5\times10^{-6}\,\Omega\,\mathrm{cm}^2$ for the sample with a carrier concentration of $8.1\times10^{19}\,\mathrm{cm}^{-3}$. This is a very low ohmic contact resistance reported for p-type GaN. The effect of annealing on these Be-implanted samples was also investigated. These samples were annealed under the same optimal annealing conditions as the nonimplanted as-grown p-type GaN samples described previously. The I–V curves of the annealed samples become nonlinear and the specific resistance also increased after annealing. We have not yet determined the exact cause of this. However, the reaction of Be atoms with O_2 may be one of the possible factors.

In summary, we reported the demonstration of low resistance ohmic contacts to p-type GaN samples using Ni/Pd/Au metallization scheme. For as-grown Mg-doped p-type GaN with low carrier concentration, we obtained a specific contact resistance as low as $1.0\times10^{-4}\,\Omega\,\mathrm{cm}^2$ by annealing the samples in oxygen ambient at 550 °C for 5 min. For the Be-implanted p-type GaN samples, a lowest ohmic contact resistance value of $4.5\times10^{-6}\,\Omega\,\mathrm{cm}^2$ was achieved without further annealing process. This Au-based Ni/Pd/Au metallization contact should be suitable for making low resistance ohmic contact to either low carrier concentration

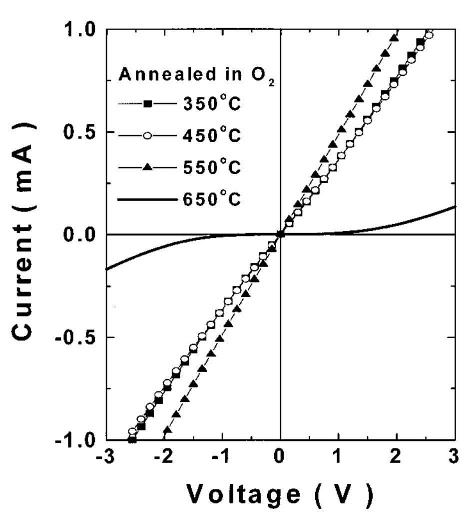

FIG. 2. Current–voltage (I–V) characteristics of Ni/Pd/Au contacts annealed in oxygen for different annealing temperatures.

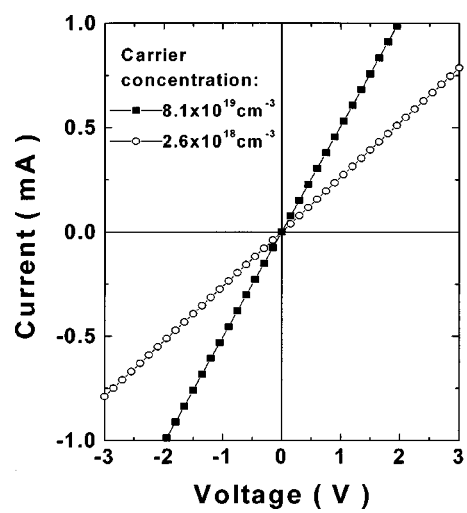

FIG. 4. Current–voltage (I–V) characteristics of Ni/Pd/Au contacts on Be-implanted p-type GaN.

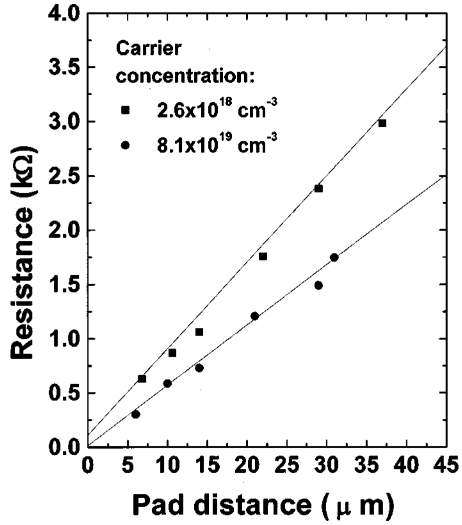

FIG. 5. Plot of the measured total resistance against the contact pad spacing for Ni/Pd/Au contacts on Be-implanted *p*-type GaN.

(10^{15}–$10^{17}\,cm^{-3}$) or high carrier concentration ($>10^{18}\,cm^{-3}$) *p*-type GaN.

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