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Very-Low-Specific-Resistance Pd/Ag/Au/Ti/Au Alloyed Ohmic Contact to p GaN for High-Current Devices

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Very-low-specific-resistance Pd/Ag/Au/Ti/Au alloyed ohmic contact to *p* GaN for high-current devices

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We report on Pd/Ag/Au/Ti/Au alloyed metallic contact to *p* GaN. An 800 °C anneal for 1 min in flowing nitrogen ambient produces an excellent ohmic contact with a specific contact resistivity close to $1\times10^{-6}\,\Omega\,\mathrm{cm}^2$ and with good stability under high current operation conditions. This high-temperature anneal forms an alloy between Ag, Au, and *p* GaN resulting in a highly *p*-doped region at the interface. Using x-ray photoelectron spectroscopy and x-ray diffraction analysis, we confirm that the contact formation mechanism is the metal intermixing and alloying with the semiconductor. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1353813]

The development of low-specific resistance and high-current carrying capability ohmic contacts to Mg doped *p* GaN are one of the major challenges for the high power III–V nitride light emitting diodes (LEDs), laser diodes, bipolar junction transistors, and heterojunction bipolar transistors. A relatively low *p* doping ($<1\times10^{18}\,\mathrm{cm}^{-3}$) in *p* GaN, achievable either by metalorganic chemical vapor deposition (MOCVD) or molecular beam epitaxy makes it very difficult to form such *p*-ohmic contacts. To date, best *p*-contact resistivity of $4\times10^{-6}\,\Omega\,\mathrm{cm}^2$ has been reported using Ni/Au[1,2] and Pd/Au[3,4] with oxygen annealing. In the past, several other metal combinations, such as Au,[5,6] Ni,[7,8] Pd,[9] Pt,[7,10] Ni/Au,[10–14] and Pt/Ni/Au,[15,16] have also been studied. Lee and co-workers[4] reported on the surface treatment using boiling aquaregia. This oxidation–reduction reaction, widely used in GaAs technology, improved the contact resistivity by two orders of magnitude to approximately $4.3\times10^{-4}\,\Omega\,\mathrm{cm}^2$. Nearly all the contact schemes reported to date, employ annealing temperatures in the 450–500 °C range. This low-temperature annealing precludes any melting of the contact metals and prevents the reaction of this metallic alloy with the surface of *p* GaN.

In this letter, we report on Pd/Ag/Au/Ti/Au contact to *p* GaN fabricated using an 800 °C anneal in nitrogen ambient. This high temperature anneal results in the formation of an alloy of Ag and Au, which, in turn, reacts with the top *p*-GaN surface forming a p^+ region at the metal–semiconductor interface. Consequently, the resulting *p*-ohmic contact has greatly improved temperature stability, a significantly smaller metal spreading resistance, and superior ohmic characteristics. Using this Pd/Ag/Au/Ti/Au contact scheme, we measure a specific contact resistivity as low as $1.1\times10^{-6}\,\Omega\,\mathrm{cm}^2$. Our reported *p* contact is similar in nature to the high-temperature annealed (anneal temperature >850 °C). Ti/Al contacts to *n* GaN and *n* AlGaN, where the metal and semiconductor are shown to react and form Al_3TiN[17] and various other[18,19] complexes. These complexes produce an interfacial n^+ layer with high *n*-type doping, thereby assisting in the formation of the *n*-ohmic contact. In this letter, we also demonstrate the stability of our Pd/Ag/Au/Ti/Au metallic contact under high-current operation by using it for a vertically conducting GaN–InGaN multiple quantum well (MQW) LED structure grown on a SiC substrate.

The *p*-GaN films used in this study were grown by low-pressure MOCVD on (0001) sapphire substrate. Trimethylaluminum, Triethylgallium, Bis-cyclopentadienylmagnesium, and Ammonia were used as Al, Ga, Mg, and N source materials, respectively. Hydrogen was used as a carrier gas. Firstly, a 250 Å thick AlN buffer layer was grown at 600 °C, followed by a 1 μm thick undoped highly insulating GaN layer grown at 1000 °C and 76 Torr. Finally, a 0.3 μm micron thick Mg-doped GaN layer was grown and activated by a 750 °C 20 min anneal in N_2 ambient. Room temperature Hall measurements show the hole concentration of $6\times10^{17}\,\mathrm{cm}^{-3}$ and the resistivity of $2\,\Omega\,\mathrm{cm}$.

Pd (1 nm)/Ag(50 nm)/Au (10 nm)/Ti (30 nm)/Au (20 nm) contacts were then deposited in a transmission line model (TLM) pattern using *e*-beam evaporation and standard photolithographic lift-off technique. The TLM contact pad size was 50 μm×150 μm, and the gap between the pads varied from 2 to 14 μm. These *p* contacts were then annealed at a temperature of 800 °C for 1 min in nitrogen ambient using a rapid thermal annealing system. The selection of our contact metals and the high temperature anneal is based on the realization that Ag and Au form an alloy at a temperature of about 773 °C.[20,21] This temperature is also close to the temperature required for *p*-GaN activation and is less than the upper limit at which the optical emission characteristics of InGaN/GaN MQW degrade. The Pd layer in our contacting scheme was included to improve the adhesion of the Ag layer to the surface of *p* GaN.

The current–voltage ($I-V$) characteristics were measured between the two TLM contact pads separated by a 2 μm gap. As seen from Fig. 1(a), the contacts were linear

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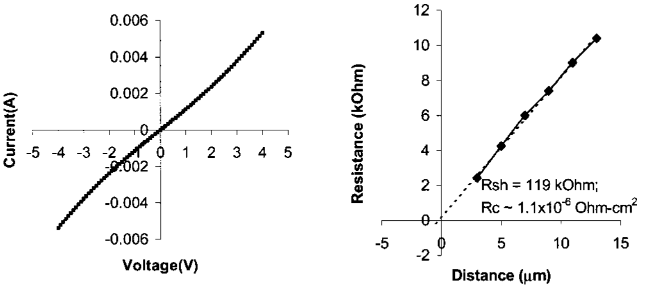


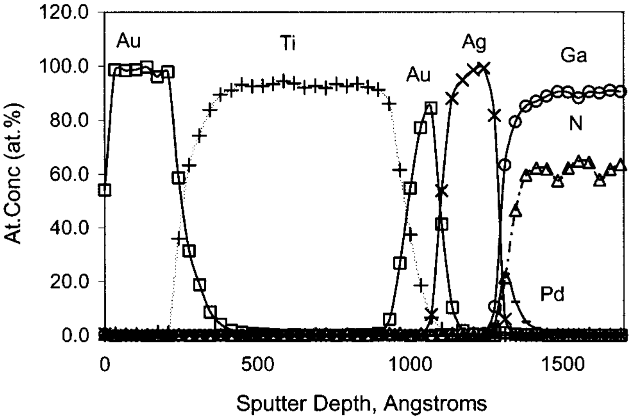
(a) (b)

FIG. 1. *I–V* curve (a) and TLM plot (b) for annealed Pd/Ag/Au contact.

even at voltages below 1 V, thus proving the absence of a Schottky barrier at the metal–semiconductor interface. Figure 1(b) shows the resistance between contact pads as a function of the spacing. From these TLM data, we calculated the specific contact resistance to be about $1\times10^{-6}\,\Omega\,\mathrm{cm}^2$. (A high sheet resistance of *p* layer, which is of the order of 100 kΩ makes it difficult to determine these low contact resistances with a very high degree of accuracy.)

In order to study the contact formation mechanism, we performed an x-ray photoelectron spectroscopy (XPS) analysis of our samples. The results of this XPS study are depicted in Fig. 2. Figures 2(a) and 2(b) show the profiles of Pd, Ag, Au, and Ti layers before and after the 800 °C anneal, respectively. It is clearly observed that the 800 °C anneal results in an extensive intermixing of the various metals. Further, as seen from Fig. 2(b), after the anneal, Ag, and Au layers have nearly identical profiles of concentration distribution indicating an alloy formation adjacent to the GaN surface. The data of Fig. 2(b) also show that an intensive interpenetration of the (Ag/Au) alloy into *p* GaN has taken place. We thus speculate that the ohmic behavior of our contact results from the alloy formation between these two metals (Ag and Au) and from the alloy interpenetration into the top surface of the *p* GaN. According to the binary phase diagram,[20,21] two intercalation compounds, namely, Me$_2$GaN and Me$_3$GaN for Me–Ga–N (Me=Metal) metal–semiconductor interface can be formed. However, only Me$_2$GaN compound is chemically stable. Our 800 °C anneal should therefore yield a complex compound of (Ag+Au)$_2$GaN, which, we believe, creates a highly doped p^+ region at the metal and *p* GaN interface.

(a) XPS Plot for As-Deposited Contact



(b) XPS Plot of Annealed Contact

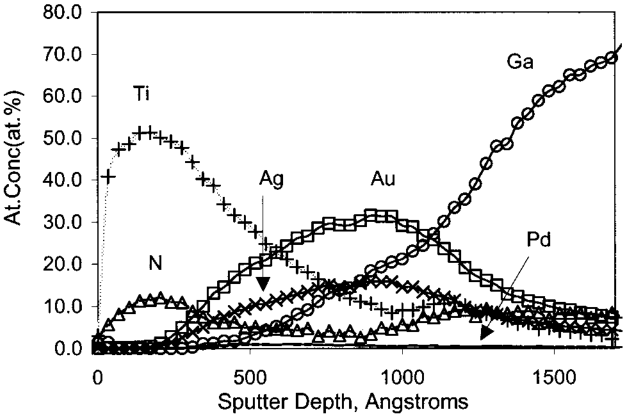


FIG. 2. XPS plot of as-deposited (a) and annealed (b) atomic concentration vs sample sputter depth for Pd/Ag/Au/Ti/Au contact.

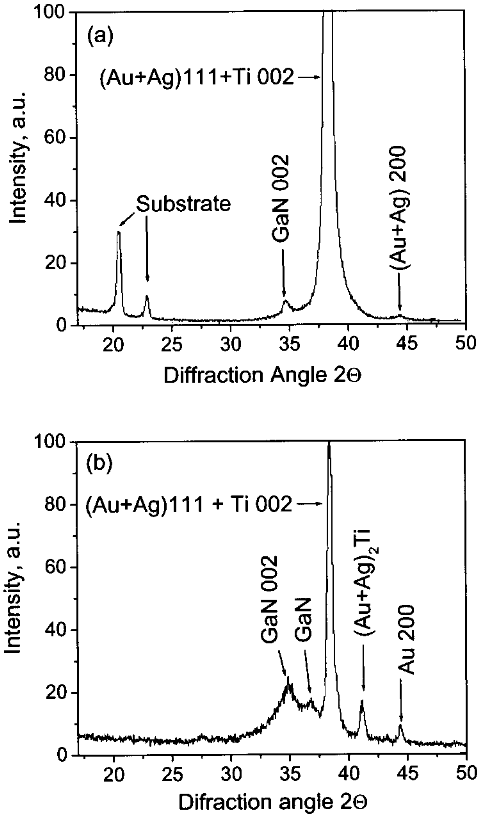


FIG. 3. XRD data of as-deposited (a) and annealed (b) contact.

In order to further confirm these XPS results and the suggested contact formation mechanism, we performed an x-ray diffraction (XRD) analysis. Figure 3(a) shows the XRD data for the as-deposited sample and Fig. 3(b) includes the XRD data after the 800 °C anneal. As seen, the (002) GaN peak has broadened out in the annealed sample indicating that the top surface of GaN is disordered by the Au/Ag diffusion. This result agrees with the XPS data discussed. However, the exact nature of the compound, which acts as creating shallow acceptors, needs further investigations.

To further confirm the (Au/Ag) interpenetration into GaN, we removed the annealed contact by boiling it in aquaregia followed by an hydrogen fluoride dip. Small pits with the same dimensions as the contact pad were observed having a depth of approximately 200–250 Å.

In order to prove the feasibility of using our Pd/Ag/Au/

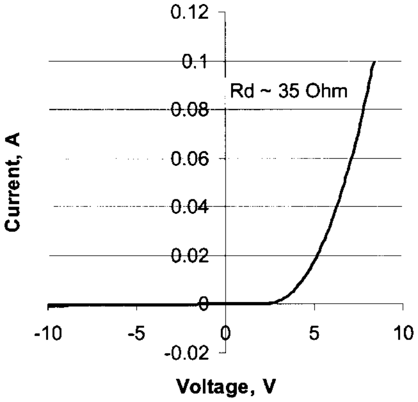


FIG. 4. dc current–voltage characteristic of $2\,\mu\text{m}\times700\,\mu\text{m}$ stripe-geometry MQW LED with Pd/Ag/Au contact. (0.1 A dc current corresponds to device current density of 7.1 kA/cm^2.)

Ti/Au contact in high-current devices, we used such *p* contact in a vertically conducting InGaN/GaN MQW LED structure grown on SiC. The epilayer structure for this MQW LED was deposited over n^+ SiC substrates using low-pressure MOCVD. It consisted of a 0.1 μm thick n^+-AlGaN buffer layer, a 0.2 μm thick Si doped n^+GaN layer ($n^+ \sim 1\times10^{18}\,\text{cm}^3$), a 500 Å thick *n*-GaN layer ($n=5\times10^{17}\,\text{cm}^{-3}$), an InGaN/GaN MQW and a 0.15 μm thick *p*-GaN ($p=5\times10^{17}\,\text{cm}^{-3}$) cap layer. The MQW region consisted of four 30 Å thick $In_{0.22}Ga_{0.78}N$ quantum wells surrounded by 30 Å thick GaN barrier layers.

The LED devices were fabricated by first forming a flat *n* contact to the n^+SiC substrate using Ni (50 Å)/Al (100 Å)/Ti (200 Å)/Au (1000 Å). The *n* contact was annealed at 850 °C for 1 min. Finally, stripe-geometry ($2\,\mu\text{m}\times700\,\mu\text{m}$) Pd/Ag/Au/Ti/Au *p*-ohmic contacts were formed on the top of the *p* layer using the described procedure. Figure 4 shows the $I-V$ characteristics of this stripe-geometry MQW LED under dc pumping. As seen from Fig. 4, the Pd/Ag/Au/Ti/Au contacts can easily support the current density as high as 7 kA/cm^2. No contact degradation was observed for this high-current operation. The device shown in Fig. 4 demonstrated stable emission with the peak emission wavelength $\lambda_p = 410\,\text{nm}$ and a full width at half maximum of 12 nm.

In summary, we report on Pd/Ag/Au/Ti/Au ohmic contact to *p* GaN. Using a 1 min 800 °C anneal in N_2 ambient, the contact resistivity as low as $1\times10^{-6}\,\Omega\,\text{cm}^2$ was achieved. XPS and XRD data are presented to establish the contact formation mechanism, which was forming an Ag/Au alloy with its subsequent interpenetration into the *p*-GaN surface region. We also demonstrate the stability of our new Pd/Ag/Au/Ti/Au contact under high-current operation by using this contact for a *pn*-junction InGaN/GaN MQW LED operating at current densities as high as 7.1 kA/cm^2.

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