Ohmic contacts to *n*-GaN using $PtIn_2$

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A new metallization scheme has been developed to form Ohmic contacts to *n*-GaN. Contacts were fabricated by sputtering the intermetallic compound, $PtIn_2$ on metal–organic vapor phase epitaxy grown *n*-GaN ($n \sim 5\times10^{17}$ cm^{-3}) with some of the contacts subjected to rapid thermal annealing. Contacts in the as-deposited state exhibited nearly Ohmic behavior with a specific contact resistance of 1.2×10^{-2} Ω cm^2. Contacts subjected to rapid thermal annealing at 800 °C for 1 min exhibited linear current–voltage characteristics and had specific contact resistances less than 1×10^{-3} Ω cm^2. Auger depth profiling and glancing angle x-ray diffraction were used to examine the interfacial reactions of the $PtIn_2$/*n*-GaN contacts. Consistent with estimated phase diagram information, the results from Auger depth profiling and glancing angle x-ray diffraction indicated the formation of $(In_xGa_{1-x})N$ at the contact interface, which could be responsible for the Ohmic behavior of $PtIn_2$ contacts. © *1997 American Institute of Physics.* [S0003-6951(97)00201-5]

GaN is a III–V compound semiconductor with a wurtzite crystal structure having a 3.4 eV direct energy band gap at room temperature. When alloyed with the other group III nitrides, GaN can form a continuous alloy system whose room temperature band gaps range from 1.9 eV (InN) to 6.2 eV (AlN).[1] This makes GaN a very suitable material for optoelectronic devices, such as light emitting diodes (LEDs), performing in the blue and ultraviolet regions.

Despite its promise, GaN was useless for high efficiency optical devices due to the inability to grow *p*-type GaN films. That is until recently, when success in obtaining *p*-type GaN films lead to renewed and intense interest in GaN.[2] Blue and blue–green LEDs are commercially available from Nichia Chemical Industries with a luminosity of 2 cd and central wavelengths from 450 to 500 nm.[3] Nichia has also demonstrated a nitride laser operating at 416 nm.[4] Additionally, Cree Research announced the development of GaN LEDs that operate at 430 nm and produce 500 μW output at 20 mA.[5] GaN has also been used for junction field effect transistors[6] and high electron mobility transistors.[7]

Even with the successes of GaN devices there is much more work to be done. High contact resistance can substantially reduce the performance of GaN optical and electrical devices; therefore, to obtain optimum performance the contact resistance should be minimized. The present technology for the formation of Ohmic contacts to *n*-GaN usually involves the use of Ti or Al metallization schemes.[8–10] In this letter, we report the results of a different type of metallization scheme, one utilizing $PtIn_2$. $PtIn_2$ is a intermetallic compound with a CaF_2 (C1) crystal structure, good chemical stability, and a peritectic melting point at 1039 °C.[11]

Based on binary phase diagram data and the estimated ternary phase diagrams of the Pt–In–Ga–N system, $PtIn_2$/GaN meets the thermodynamic criteria formulated by Jan[12] and Chang[13] for participating in the exchange reaction. The solid-state exchange reaction has been identified as a systematic approach for tailoring metal/semiconductor contact properties.[14] During the exchange reaction, one element in the metal phase exchanges with another element in the semiconductor without the formation of new phases. When $PtIn_2$/GaN contacts are annealed there should be an exchange of In and Ga atoms at the interface, producing $(In_xGa_{1-x})N$ and $Pt(In,Ga)_2$ at the interface. The formation of $(In_xGa_{1-x})N$ at the contact interface is the proposed mechanism for the Ohmic behavior of $PtIn_2$/*n*-GaN contacts.

The following procedures were used to prepare all samples examined in this study, with the lithography being omitted on substrates not used for electrical measurements. The *n*-GaN substrates used in this study are thin layers (2–3 μm) of single crystal GaN on sapphire (0001) with a 10–20 nm AlN buffer layer grown by metal–organic vapor phase epitaxy.[15] The *n*-GaN epilayer is typically unintentionally doped to 5×10^{17} cm^{-3} with a sheet resistance of 1000 $\Omega/\square$. Prior to the lithography, the substrates where ultrasonically degreased with trichloroethylene, acetone, and methanol for 5 min each. The substrates were then dipped into a H_2SO_4:H_3PO_4 (1:1) solution and rinsed in H_2O. Using standard photolithographic techniques, the substrates were patterned with one of three masks. For the *I–V* measurements, equally spaced circular dots 400 μm in diameter and 550 μm apart were used. For specific contact resistance (ρ_c) measurements, a circular transmission line model (TLM) pattern[16] or a four-point probe pattern consisting of circular dots 150 μm in diameter and 750 μm apart was used. The patterned substrates were then placed in a BOE solution for 5 min, rinsed in de-ionized water, and immediately loaded into a vacuum chamber with the background pressure less than 4×10^{-7} Torr.

Nominally 150 nm $PtIn_2$ films were deposited onto the substrates by a dc magnetron sputtering from a single alloy target. X-ray diffraction was used to confirm that the sputtered film's crystal structure matched that of $PtIn_2$. After the sputter deposition, the photoresist was lifted off in an acetone bath leaving the patterned metallization on the wafers. Following lift-off, samples were annealed in an AG Associ-

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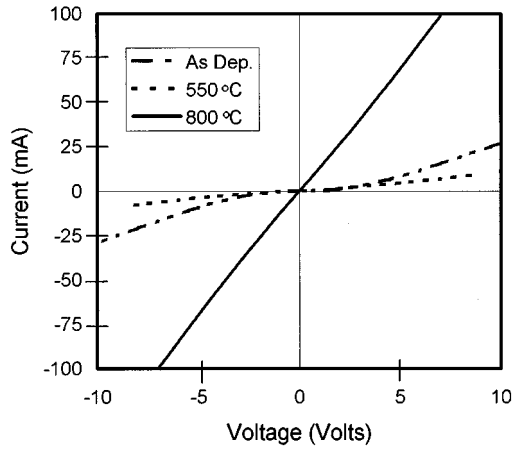

FIG. 1. Current–voltage characteristics of $PtIn_2$ contacts on *n*-GaN with varied annealing conditions. All contacts were annealed for 1 min.

ated MiniPulse rapid thermal annealing system with a flowing high purity Ar atmosphere.

After annealing, *I–V* data were measured with a Keithley Model 236 electrometer. Figure 1 shows the *I–V* characteristics of the $PtIn_2/n$-GaN contacts for three different annealing conditions. These data show that even the as-deposited contacts do not exhibit rectifying behavior. When the contacts are annealed at 550 °C for 1 min they exhibit a more linear *I–V* behavior than the as-deposited contacts, but the contact resistance increases. In contrast, the contact resistance is lower for the contacts annealed at 800 °C for 1 min. Also, the contacts subjected to this annealing condition exhibit nearly linear *I–V* characteristics.

While the *I–V* characteristics shown in Fig. 1 are useful for examining changes in contact behavior with temperature, measuring the specific contact resistance (ρ_c) gives more quantitative information. Additionally, it allows for the comparison of contacts with different types of geometry and shows if the metallization could be used for practical device fabrication, where resistance values of mid-10^{-6} Ω cm^2 are often considered device quality.[17]

In this study a circular TLM was utilized to measure the ρ_c.[16] This method requires the resistance of the metal layer to be small compared to the resistance of the substrate. However, due to the relatively high electrical resistivity of $PtIn_2$ ($\sim 1.5\times10^{-4}$ Ω cm), it was not possible to measure a resistance that would be valid for the TLM. To solve this problem a more conductive second layer, 100 nm of Au, was thermally evaporated on top of the $PtIn_2$ metallization. While this was a very effective way of attaining the as-deposited measurement, Auger depth profiles showed that Au reacts extensively with $PtIn_2$ when annealed at 800 °C for 1 min. Co and W were also examined as metals for the conductive layer, but it was found that they also react with $PtIn_2$. The reaction between the two metal layers could affect the In–Ga exchange reaction, thus, a different measurement technique was required.

To measure the ρ_c's of the annealed substrates a modified four-point probe method was employed.[18] This method is not as sensitive to the resistance of the metallization as the TLM, however, the sheet resistance of the GaN substrate

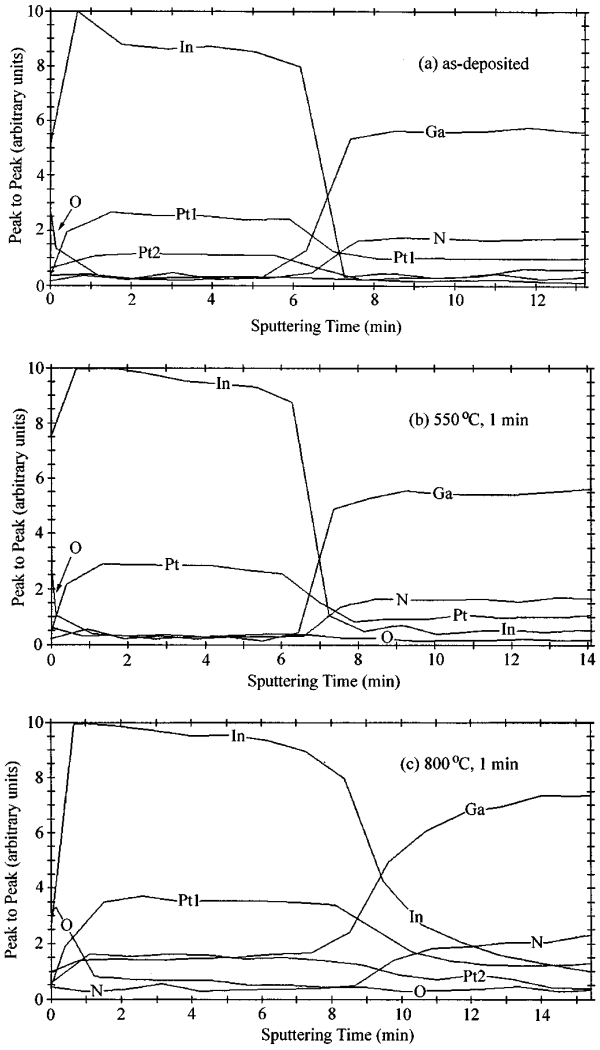

FIG. 2. Auger depth profiles of $PtIn_2/n$-GaN (a) as-deposited state (b) annealed at 550 °C for 1 min and (c) annealed at 800 °C for 1 min.

greatly limits the range of contact resistance that can be measured. Once the contact's resistance is small compared to the sheet resistance of the substrate, the error in the measurement becomes large. For the substrates and the size of contact pads used in this study, the lower limit for a reliable ρ_c measurement is approximately 1×10^{-3} Ω cm^2.

For as-deposited contacts, a 1.2×10^{-2} Ω cm^2 ρ_c was measured using TLM. This is as low as as-deposited Al- and Ti-based metallization schemes on *n*-GaN films that were not subjected to reactive ion etching.[8–10] Contacts annealed at 800 °C for 1 min, measured using the four-point probe method, showed a significant decrease in specific contact resistance with values below 1×10^{-3} Ω cm^2, which is the resolution limit of the four-point probe method.

In addition to the electrical measurements, Auger depth profiling and glancing angle x-ray diffraction (GAXRD) were used to characterize the interfacial reaction of the contacts. The Auger depth profiles on the as-deposited and annealed contacts were done using a Perkin–Elmer scanning electron microprobe. GAXRD was carried out with a Nicolet diffractometer utilizing Cu $K\alpha$ radiation.

Auger depth profiles were done on $PtIn_2/n$-GaN both in the as-deposited state and after two different annealing con-

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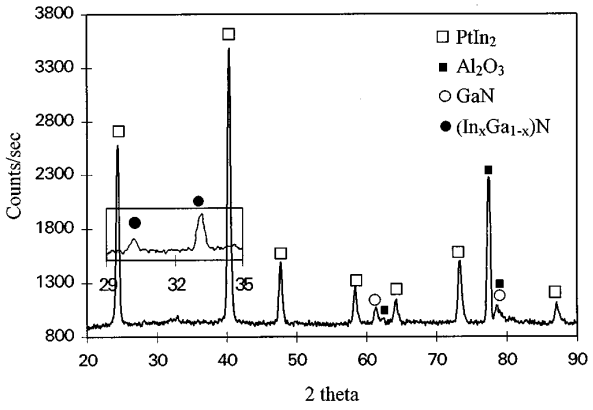

FIG. 3. Glancing angle x-ray diffraction pattern of $PtIn_2/n$-GaN annealed at 800 °C for 1 min. The box inside this figure shows a second diffraction pattern taken under the same conditions using a slower scan rate to resolve the low intensity peaks.

ditions: 550 and 800 °C both for 1 min. The Auger depth profile of the as-deposited contact, Fig. 2(a), shows a relatively sharp interface between $PtIn_2$ and GaN. Figure 2(b) shows the effect of annealing at 550 °C for 1 min. This demonstrates clearly that there is little or no change in the contact interface when compared to the as-deposited sample. If there is any reaction at the interface under this annealing condition, as the electrical measurement suggests, it must be on a scale too small for this technique to resolve. In contrast, Fig. 2(c) does not show a sharp interface. It has a broad region where In and Ga are both present and the Pt level is decreasing while the N level is increasing, suggesting the formation of $(In_xGa_{1-x})N$. The Auger depth profiles are, thus, consistent with the proposed reaction, which predicts the formation of interfacial $(In_xGa_{1-x})N$ during annealing.

The GAXRD pattern of $PtIn_2/n$-GaN annealed at 800 °C for 1 min, shown in Fig. 3, was done with the angle between the incident x ray and the substrate (omega) held at a constant 8°. The box inside Fig. 3 shows a second diffraction pattern taken under the same conditions using a slower scan rate to resolve some of the low intensity peaks. While a number of angles were tried (4°–10°), the 8° pattern was included in the letter because it shows the most overall information. Four phases were identified in Fig. 3: $PtIn_2$, GaN, Al_2O_3 and $(In_xGa_{1-x})N$. Diffraction patterns, taken at the same omega, of the $PtIn_2$ metallization sputtered on a Si, GaN epilayer and Al_2O_3 substrate were used as standards to be compared to the pattern of the annealed sample. The remaining peaks, those not matching the standards, were found to be consistent with $(In_xGa_{1-x})N$.

In summary, using $PtIn_2$ we have fabricated low resistance Ohmic contacts to *n*-GaN. For as-deposited contacts a 1.2×10^{-2} Ω cm^2 ρ_c was measured using TLM. Contacts annealed at 800 °C for 1 min had linear I–V characteristics and showed a significant decrease in ρ_c with values below 1×10^{-3} Ω cm^2 as measured by the four-probe method. Auger depth profiles and GAXRD were used to characterize the interfacial reactions between $PtIn_2$ and *n*-GaN. The results of both the Auger depth profiles and GAXRD on contacts annealed at 800 °C for 1 min suggest the formation of $(In_xGa_{1-x})N$ through a solid-state reaction at the contact interface. The formation of $(In_xGa_{1-x})N$ was expected based on the estimated phase diagram information, and the authors propose it is the $(In_xGa_{1-x})N$ that is responsible for the contact's Ohmic behavior.

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