Indium tin oxide contacts to gallium nitride optoelectronic devices

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We have fabricated GaN-based light-emitting diodes using transparent indium tin oxide (ITO) *p* contacts. ITO-contacted devices required an additional 2 V to drive 10 mA, as compared to similar devices with metal contacts. However, ITO has lower optical absorption at 420 nm ($\alpha = 664\ \mathrm{cm}^{-1}$) than commonly used thin metal films ($\alpha = 3\times10^{5}\ \mathrm{cm}^{-1}$). Uniform luminescence was observed in ITO-contacted devices, indicating effective hole injection and current spreading. © *1999 American Institute of Physics.* [S0003-6951(99)01626-5]

High electrical conductivity and transparency to visible light have made indium tin oxide (ITO) a useful material for transparent contacts to many optoelectronic devices. Rectifying contacts to silicon-, GaAs-, and InP-based solar cells and metal–semiconductor–metal (MSM) photodetectors have already been demonstrated.[1–3] Of particular interest, however, has been the use of a nonrectifying ITO contact as a current-spreading layer in AlInGaP light-emitting diodes (LEDs)[4] and as an intracavity contact in AlInGaAs vertical cavity lasers (VCSELs).[5,6]

Light emitters and detectors based on the ZnSe and GaN material systems and operating in the green, blue, and ultraviolet range of the spectrum are rapidly becoming available, and many could benefit from transparent contacts. However, contacting wide band-gap semiconductors is difficult, and reports of transparent contacts in these systems are scarce. ITO ohmic contacts to ZnSe have been demonstrated,[7] as well as Schottky contacts to *n*-GaN.[8] A transparent, ohmic contact to *p*-GaN would be particularly useful, since the poor lateral conductivity of *p*-GaN precludes the use of a ring contact. We report here the use of ITO as a contact to *p*-GaN, and demonstrate effective current-spreading and low optical loss in the blue/violet wavelength range. We also compare ITO to thin metal for use as transparent contacts.

Two GaN films were used in our experiments—both grown by metalorganic chemical vapor deposition (MOCVD) on sapphire substrates. The layer structure for the first was as follows: 3 μm of silicon-doped GaN, five quantum wells consisting of 5 nm silicon-doped $In_{0.04}Ga_{0.96}N$ barriers and 3.5 nm undoped $In_{0.14}Ga_{0.86}N$ wells, and a 180 nm magnesium-doped *p* layer. The second film had a similar structure only with 7.5 nm GaN barriers and 2.5 nm $In_{0.2}Ga_{0.8}N$ wells, a 40 nm magnesium-doped $Al_{0.2}Ga_{0.8}N$layer, and a thicker *p* layer (300 nm). The dopant level in the *p* layer for both films was around $5\times10^{19}\ \mathrm{cm}^{-3}$, and the hole concentration (in bulk material) was approximately $7\times10^{17}\ \mathrm{cm}^{-3}$ after activation at 950 °C for 3 min.[9] We note that although the active region differed, the characteristics of the contact should only be a function of the top *p*-layer quality, and as such we can compare similar devices on these two wafers.

The ITO films and contacts were deposited in a dc ring magnetron sputtering system with a target to sample distance of 12 cm, in a 9 mTorr argon/oxygen plasma, with gas flows of 45 and 0.25 sccm, respectively. The target was high density (95%) ITO with an indium oxide to tin oxide ratio of 90/10. The power density at the target was 6 W/cm^2, and the deposition rate at the substrate was approximately 20 nm/min. A liftoff process was used to define the ITO contacts. The deposited films looked dark brown, but became transparent after a rapid thermal anneal (RTA) at 600 °C for 2 min in a nitrogen ambient. Anneals at 500 °C resulted in contacts with higher turn-on voltages and larger leakage currents, while contacts annealed at 700 °C were significantly more resistive. ITO films annealed at all three temperatures exhibited identical optical characteristics (absorption and refractive index).

The ITO thickness was chosen to be 25 nm in order to minimize absorption in the films—a necessity for vertically emitting lasers. Using transmission line method (TLM) patterns, we obtained the bulk resistivity for ITO, $\rho = 5.4\times10^{-4}\ \Omega\,\mathrm{cm}$, in good agreement with values reported elsewhere.[10] Additionally, we found that no degradation of the films occurred for lateral currents of up to 300 mA in 50 μm wide stripes.

To verify hole injection, we fabricated broad-area ($200\times200\ \mu$m) LEDs with a 25 nm ITO *p*-contact, and for comparison, devices with 5/6 nm Ni/Au instead of ITO. Square Ti/Au probe pads were placed in a corner of the devices. The ITO/Ti/Au *p* contacts were ohmic, with a specific contact resistivity of $3\times10^{-4}\ \Omega\,\mathrm{cm}$. Contacts to the *n* layer were Ti/Al/Ni/Au and ohmic. As shown in Fig. 1, the ITO-contacted devices (on the material with thicker *p*-GaN) required 6 V to drive 10 mA. The metal-contacted devices required 2 V less, and had about two thirds of the slope resistance. However, the turn-on voltage varied with device geometry, and the slope resistance did not scale inversely with area.[11] Smaller devices, with a 20 μm diameter circular ITO contact and a ring Ti/Au pad [Fig. 2(b)], showed turn-on voltages of around 7.5 V with a slope resistance of approxi-

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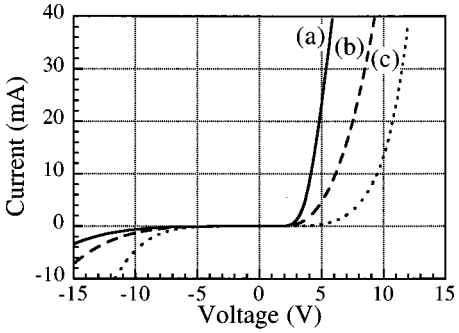

FIG. 1. *I–V* curves of broad area LEDs (200×200 μm) with different *p* contacts: (a) 5/6 nm Ni/Au, (b) 25 nm ITO annealed at 600 °C, and (c) 25 nm ITO annealed at 500 °C.

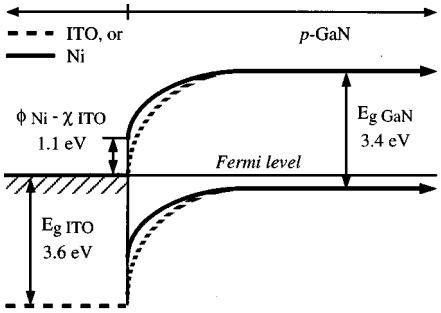

FIG. 3. Equilibrium band diagram schematic for ITO/*p*-GaN and Ni/*p*-GaN. The difference indicated is the work function (ϕ) of Ni minus the electron affinity (χ) of ITO. The band-gap energies (E_g) for GaN and ITO are also noted.

mately 100 Ω. Blue electroluminescence was observed, indicating hole injection into the quantum wells. The luminescence from these devices however, looked spotty.

20 μm diameter devices fabricated on the wafer with a slightly thinner (180 nm) *p*-GaN layer had a higher turn-on voltage. ITO-contacted LEDs turned on around 10 V, with a slope resistance of approximately 190 Ω, and again exhibited a 2 V increase over metal-contacted devices. The luminescence (with peak wavelength of 420 nm and linewidth of 20 nm) was uniform and emanated from underneath the ITO layer, indicating effective current spreading from the ring metal pad to the center of the ITO window. Figure 2 shows a picture taken of a luminescing device. The light intensity exhibited superlinear variation with current, a known phenomenon in GaN LEDs.[11]

Figure 3 shows a schematic of the band structure for the *p*-GaN contacts.[12] Since the work function for nickel is approximately 5.2 eV,[13] while for ITO (a degenerate n^+ semiconductor), the electron affinity is around 4.1 eV,[14] we should expect a voltage penalty of 1 V or less. It should also be noted that the reverse bias characteristics also show a 2 V difference, suggesting the presence of a barrier in either direction. We suspect that on the samples with spotty emission, the regions of increased light emission correlate with regions of low contact resistance. The variations may be due to either nonuniformity in the *p* doping of the GaN, or to a process-related problem such as a partial deactivation of the doping at the GaN surface or formation of a thin gallium oxide layer during the ITO sputtering. We note that *p* doping of GaN is still a developing technology, and that contact to both metal and ITO should continue to improve.

Optical transmission was measured on ITO films deposited on polished sapphire substrates. We have measured both transmission and reflection, from which the loss can be calculated: $T+R+L=1$. The results are shown in Fig. 4, for a 25 nm ITO film, annealed at 600 °C for 2 min, and for a 5/6 nm Ni/Au film. At 420 nm, a typical wavelength for InGaN quantum well lasers, the transmission and reflection add up to 99%. If this loss is completely due to absorption, it corresponds to a power absorption coefficient, α, of 3800 cm^{-1}. However, calculations of α from $R+T$ are prone to error when measuring such thin films (25 nm). A more accurate ellipsometry measurement for this film (on silicon) yielded a refractive index of 2.06 and an absorption coefficient of 664 cm^{-1} ($R+T=99.8\%$), at 420 nm. For comparison, the Ni/Au film had $R+T=65\%$ ($\alpha=3\times10^5$ cm^{-1}) at this wavelength.

In conclusion, we have shown that ITO can serve as an effective current spreading layer, with low optical absorption at 420 nm, providing hole injection into GaN-based light

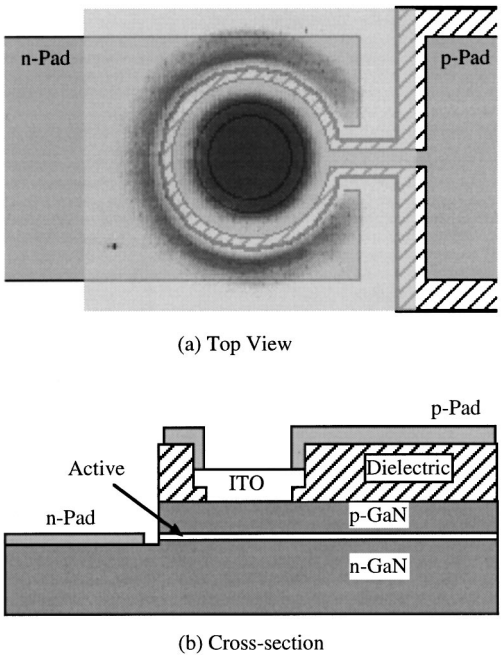

FIG. 2. (a) Overlay of luminescence photo of a 20 μm diameter device on top of schematic. The outer ring luminescence is light scattered from the mesa sidewalls. (b) Cross section of the device.

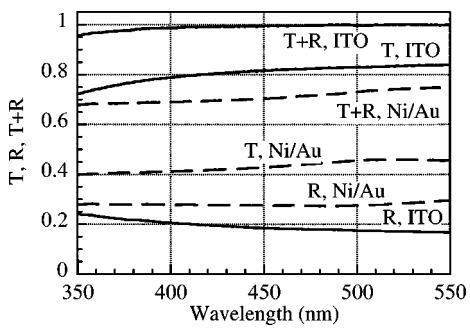

FIG. 4. Reflection, transmission, and sum curves for a 25 nm ITO film (solid lines) and for 5/6 nm Ni/Au (dashed). Both films on double-side polished sapphire.

emitters. We observed a 2 V increase in operating voltage as compared to a metal contact, higher than predicted by the electron affinity of ITO. We expect that the contact will improve as GaN doping and processing technologies are refined.

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