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LETTER TO THE EDITOR

InGaN/GaN light-emitting diodes with ITO p-contact layers prepared by RF sputtering

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Abstract
Indium tin oxide (250 nm) and Ni(5 nm)/Au(10 nm) films were successfully deposited onto both glass substrates and p-GaN epitaxial layers. The normalized transmittance of the as-deposited ITO film was 90.6% at 450 nm, which was much larger than that of Ni/Au film. The transmittance of the RF sputtered ITO film could be increased to 97.8% with *in situ* annealing. *In situ* annealing of ITO films would also improve the electrical properties of ITO on p-GaN. Nitride-based light-emitting diodes (LEDs) were also fabricated. It was found that the 20 mA forward voltage was 3.16 V, 5.74 V and 4.28 V for the LEDs with Ni/Au, as-deposited ITO and *in situ* annealed ITO p-contact layer, respectively.

III–V nitride semiconductor materials have a wurtzite crystal structure and a direct energy bandgap. At room temperature, the bandgap energy of AlInGaN varies from 0.7 eV to 6.2 eV depending on its composition [1–2]. Therefore, III–V nitride semiconductors are particularly useful for light-emitting diodes (LEDs) in the short wavelength region [3–5]. Although these nitride-based LEDs are very successful, poor ohmic contact at metal/p-GaN interface is still a problem. In order to achieve high-performance nitride-based LEDs, it is required to reduce contact resistance and enhance transmission efficiency of p-contact metal layer. Conventional nitride-based LEDs use semi-transparent Ni/Au on Mg-doped GaN as the p-contact material. However, the transmittance of such semi-transparent Ni/Au(5 nm/10 nm) contact is only around 60–75%. One possible way of solving this problem is to use transparent indium tin oxide (ITO), instead of Ni/Au, as the p-contact material. It is known that ITO is a hard and chemically inert transparent material with a high electrical conductivity and a low optical absorption coefficient. The adhesion between ITO and GaN is also good. These properties make ITO an attractive material for the fabrication of GaN-based LEDs. In fact, ITO has already been used in AlGaInP-based LEDs as the transparent upper p-contact material [6]. However, it has also been shown that good ohmic contact is difficult to achieve for ITO deposited on p-GaN [7–9]. Earlier, Margalith *et al* have reported the fabrication of nitride-based LED using ITO as the p-contact material [8]. They used a DC ring magnetron sputtering system to deposit the ITO films followed by an *ex situ* 600 °C rapid thermal annealing in nitrogen ambience for 2 min. They fabricated broad area (i.e. 200 μm × 200 μm) LEDs with ITO as the p-contact and found that the device needs 6 V to drive 10 mA. Such values are too large for practical device applications. In this study, we deposited 250 nm ITO films by RF sputtering and Ni(5 nm)/Au(10 nm) films

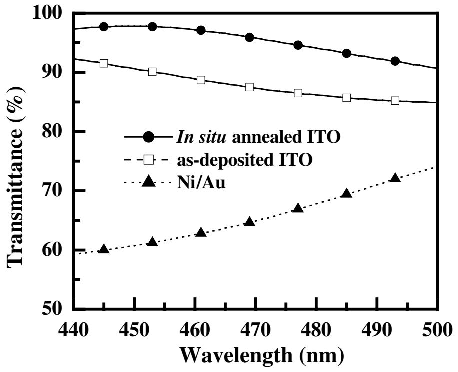

Figure 1. Optical transmittance as a function of wavelength for Ni(5 nm)/Au(10 nm), as-deposited ITO(250 nm) and *in situ* annealed ITO(250 nm) films. In this figure, the transmittance of each film was corrected taking into account the absorption of the glass substrate.

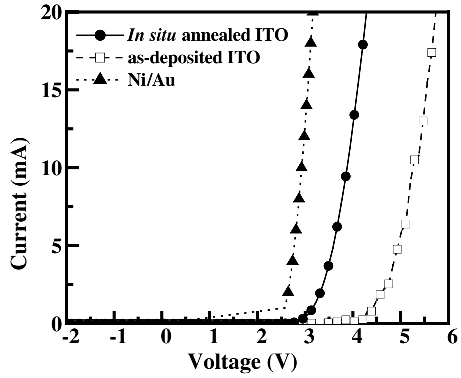

Figure 2. I–V characteristics of LEDs with Ni/Au, as-deposited ITO and *in situ* annealed ITO p-contacts.

by thermal evaporation onto p-GaN. The optical and electrical properties of these thin contact layers were investigated. Furthermore, nitride-based LEDs were fabricated by using these p-metal contacts. The characteristics of the fabricated LEDs will also be reported.

Samples used in this study were all grown by metallorganic chemical vapour deposition (MOCVD) [10–12]. We first prepared 30 nm thick low temperature GaN nucleation layer followed by a 2 μm thick Si-doped GaN epitaxial layer on top of the c-face (0001) sapphire substrates. The MQW active region was five-period $In_{0.3}Ga_{0.77}N$/GaN MQW structure consisting of 3 nm thick $In_{0.23}Ga_{0.77}N$ well layers and 7 nm thick GaN barrier layers. Finally, a 50 nm thick Mg-doped $Al_{0.15}Ga_{0.85}N$ layer and a 0.25 μm thick Mg-doped contact layer was grown. The as-grown samples were then furnace annealed at 750 °C in N_2 ambient to activate Mg. From secondary ion mass spectroscopy (SIMS) measurement, it was found the Mg concentration was around 3×10^{19} cm^3. From Hall measurements, we found that hole concentration of the annealed samples was about 5×10^{17} cm^3. 250 nm ITO contacts were then deposited onto p-GaN films and/or glass substrates by RF sputtering. We used an ITO target consists of 90% In_2O_3 and 10% SnO_2, and only Ar gas was introduced into the chamber. During sputtering, the chamber pressure was 0.5 Torr and the substrate temperature was kept at 200 °C. In some cases, the as-deposited ITO films were *in situ* annealed in the RF sputtering chamber at 250 °C for 30 min in vacuum. For comparison, Ni(5 nm)/Au(10 nm) contacts were also deposited onto p-GaN films and/or glass substrates by thermal evaporation. We first studied the optical properties of contacts deposited on glass substrates. Figure 1 shows optical transmittance as a function of wavelength of these contacts. In this figure, the transmittance of each film was corrected taking into account the absorption of the glass substrate. From figure 1, we can see that the transmittance of ITO was much larger than that of Ni/Au. At 450 nm, the transmittance of Ni/Au was only 60.7% while the transmittance of the as-deposited ITO was 90.6%. It was also found that the *in situ* annealing could further increase the transmittance of the deposited ITO films. At 450 nm, the transmittance of *in situ* annealed ITO could reach 97.8%. The high 97.8% transmittance observed from the *in situ* annealed ITO films suggests ITO is indeed suitable optically to serve as the upper p-contact for nitride-based LEDs. The electrical properties of the ITO layers are also important. By using the Lehighton contactless measurement system, we found that the sheet resistance of as-deposited ITO films and *in situ* annealed ITO films was 25 $\Omega/\square$ and 15 $\Omega/\square$, respectively. Such a result suggests that post-deposition *in situ* annealing could not only improve the optical transmittance of ITO film but also could reduce its sheet resistance, which is important for the current spreading of LEDs.

Nitride-based LEDs with Ni/Au, as-deposited ITO and *in situ* annealed ITO p-contacts were also fabricated. The InGaN/GaN MQW LED structure consists of a 30 nm thick GaN nucleation layer, a 2 μm thick Si-doped GaN n-cladding layer, an InGaN/GaN multiquantum well (MQW) active region, a 50 nm thick Mg-doped $Al_{0.15}Ga_{0.85}N$ p-cladding layer and a 0.25 μm thick Mg-doped GaN layer. The MQW active region consists of five periods of 3 nm thick $In_{0.23}Ga_{0.77}N$ well layers and 7 nm thick GaN barrier layers. Surface of the sample was then partially etched until the n-type GaN layer was exposed. Ni/Au, as-deposited ITO and/or *in situ* annealed ITO contact was subsequently evaporated onto the p-type GaN surface to serve as the p-electrode. On the other hand, Ti/Al/Ti/Au contact was deposited onto the exposed n-type GaN layer to serve as the n-type electrode. The size of our LEDs was 350 μm × 350 μm. Figure 2 shows the current–voltage (I–V) characteristic of the LEDs with different p-contacts. It can be seen that the LED forward voltage measured with a 20 mA current injection was 3.16 V, 5.74 V and 4.28 V for the LEDs with Ni/Au, as-deposited ITO and *in situ* annealed ITO p-contact layer, respectively. Compared to LED with Ni/Au p-contact, the much larger operation voltage of LEDs with ITO p-contact could be attributed to the poor ohmic properties for ITO deposited on p-GaN. It should be noted that these values are still much smaller than that reported by Margalith *et al* [6]. Furthermore, it was found that we could effectively reduce the LED operation voltage by post-deposition *in situ* annealing of ITO. We believe such a decrease is due to the barrier height lowing of ITO on p-GaN after *in situ* annealing. Figure 3 shows the 20 mA electroluminescence (EL) spectra of the three different kinds of LEDs. It can be seen that although the EL peak positions of these three LEDs were almost the same, the LED with *in situ* annealed ITO p-contact layer had the largest EL intensity while the LED with

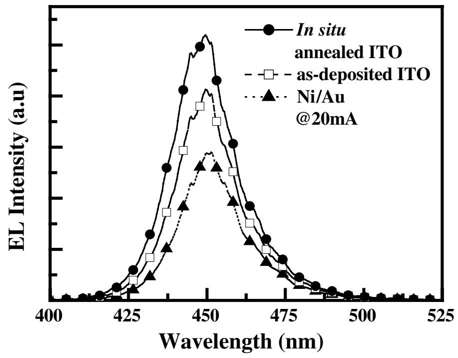

Figure 3. 20 mA EL spectra of LEDs with Ni/Au, as-deposited ITO and *in situ* annealed ITO p-contacts.

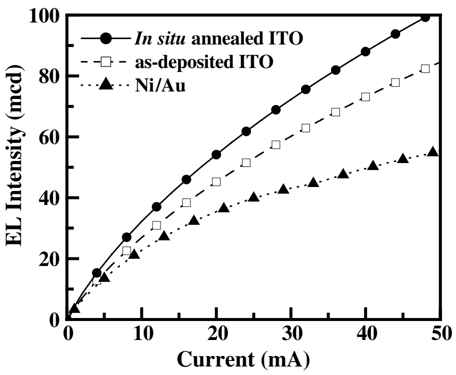

Figure 4. *L–I* characteristics of LEDs with Ni/Au, as-deposited ITO and *in situ* annealed ITO p-contacts.

Ni/Au p-contact layer had the smallest EL intensity. Such an observation agrees well with the result shown in figure 1 and could be attributed to the difference in transparency of the three different p-contact materials, since more photons can be emitted if the upper p-contact is more transparent. Figure 4 shows the EL intensity as a function of injection current of nitride-based LEDs with Ni/Au, as-deposited ITO and *in situ* annealed ITO p-contacts. With the same amount of injection current, it can be seen that the LED with *in situ* annealed ITO p-contact has the largest output EL intensity. With a 20 mA current injection, it was found that the EL intensity of LED with *in situ* annealed ITO p-contact was 55.4 mcd, which was much larger than the 35.4 mcd EL intensity observed from LED with Ni/Au p-contact. Such a significant increase in EL intensity can again be attributed to the more transparent nature of the *in situ* annealed ITO upper p-contact layer.

In summary, ITO films prepared by RF sputtering were deposited onto p-GaN and nitride-based LEDs. It was found that an *in situ* annealing of the ITO could improve both electrical and optical properties of the films. It was also found that nitride-based LEDs with ITO p-contacts show promising emission characteristics.

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