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InGaN/GaN light emitting diodes with Ni/Au, Ni/ITO and ITO p-type contacts

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Abstract

The optical and electrical properties of indium tin oxide (ITO)(60 nm), Ni(3.5 nm)/ITO(60 nm) and Ni(5 nm)/Au(5 nm) films were studied. It was found that the normalized transmittance of ITO and Ni/ITO films could reach 98.2% and 86.6% at 470 nm, which was much larger than that of the Ni/Au film. It was also found that both Ni/ITO and Ni/Au could form good ohmic contact on top of p-GaN. In contrast, ITO on p-GaN was electrically poor and non-ohmic. Nitride-based light-emitting diodes (LEDs) with these three p-contact layers were also fabricated. It was found that the LED forward voltage was 3.65, 3.26 and 3.24 V for the LEDs with ITO, Ni/ITO and Ni/Au p-contact layer, respectively. With a 20 mA current injection, it was also found that measured output power was 7.50, 6.59 and 5.26 mW for the LEDs with ITO, Ni/ITO and Ni/Au p-contact layer, respectively. Although the LED with ITO p-contact could provide the largest output intensity, its lifetime was the shortest due to severe heating effect.

Keywords: ITO; Ni/ITO; LED; InGaN/GaN; EL

1. Introduction

Group III nitride semiconductors have recently attracted much attentions for their versatile applications as high-brightness light emitting diodes (LEDs) which can be used in full-color displays, full-color indicators and light sources for lamps [1–4]. The bandgap energy of $Al_xGa_{1-x-y}In_yN$ varies from 1.9 eV, of InN, to 6.3 eV, of AlN. Therefore, one can adjust the emitting wavelength of these III nitride LEDs by changing the composition ratio between aluminum, gallium and indium. In fact, high-brightness GaN-based LEDs with spectral range from ultraviolet to amber are already commercially available. Although these nitride-based LEDs are very successful, poor ohmic contact at metal/p-GaN interface is still a problem that led to LEDs with limited performance [5–8]. In order to achieve high performance nitride-based LEDs, it is required to reduce contact resistance, enhance transmission efficiency, and improve reliability 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 contact is only around 60–75%. Although we could increase the transmittance by reducing Ni/Au metal layer thickness, the contact reliability could become an issue when the contact layer thickness becomes too small. One possible

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way to solve this problem is to use transparent indium tin oxide (ITO), instead of Ni/Au, as the p-contact material. In fact, ITO has already been used in AlGaInP-based LEDs as the transparent upper p-contact material. However, it has been reported that good ohmic contact is difficult to achieve for ITO deposited on p-GaN. The other possible way is to use Ni/ITO. Previously, Horng et al. have reported that Ni/ITO could form good ohmic contact on p-GaN [9–11]. Although ITO and Ni/ITO are both potentially useful, no report on the fabrication of nitride-based LEDs using ITO and Ni/ITO as the upper p-contact material could be found in the literature to our knowledge. In this study, we deposited ITO, Ni/ITO and Ni/Au films onto both p-GaN and glass substrates. The optical and electrical properties of these thin contact layers were then investigated. Furthermore, nitride-based LEDs were fabricated by using ITO, Ni/ITO and Ni/Au as the upper p-metal contact layers. The current–voltage (I–V), intensity–current (L–I) characteristics of the fabricated LEDs will be reported. The reliability of these LEDs will also be discussed.

2. Experiments

The p-GaN and InGaN/GaN LED samples used in this study were all grown on c-face (0 0 0 1) 2-in. sapphire (Al_2O_3) substrates in a vertical metalorganic chemical vapor deposition system. Details of the growth procedures could be found elsewhere [12–23]. During the growth, trimethylindium (TMIn), trimethylgallium (TMGa), trimethylaluminium (TMAl) and ammonia (NH_3) were used as the source materials of In, Ga, Al and N, respectively. Bicyclopentadienyl magnesium (Cp_2Mg) and silane (SiH_4) were used as the p-type and n-type doping sources, respectively. We first prepared thick Mg-doped GaN samples. After annealing the sapphire substrate at 1100 °C in H_2 ambient to remove surface contamination, a 30 nm-thick, low temperature GaN nucleation layer was deposited onto the sapphire substrate at 550 °C. The temperature was then raised to 1050 °C to grow a 2 μm-thick Mg-doped GaN p-type epitaxial layer. The growth rate of the Mg-doped GaN p-type epitaxial layer was 3 μm/h. The as-grown samples were then furnace annealed at 750 °C in N_2 ambient to activate Mg. From Hall measurements, we found that hole concentration of the annealed samples was about 5×10^{17} cm^3.

In order to measure the transmittance of the ITO, Ni/ITO and Ni/Au films, we first deposited these conducting materials onto glass substrates. ITO(60 nm) and Ni(3.5 nm)/ITO(60 nm) films were deposited onto glass substrates by electron beam evaporation at 250 °C in O_2 atmosphere without post-deposition thermal annealing. For comparison, Ni(5 nm)/Au(5 nm) films were also deposited onto glass substrates by thermal evaporation. In contrast to ITO and Ni/ITO films, the deposited Ni/Au films were then alloyed at 500 °C in N_2 atmosphere for 5 min. The transmission spectra of the deposited films were then measured by a Hitachi U3010 spectrophotometer. These conducting films were also deposited onto the p-GaN epitaxial layers. Circular transmission line model was then used to determine the specific contact resistance of these contact layers on p-GaN.

Nitride-based LEDs with these three different p-contacts were also fabricated. The InGaN/GaN multiquantum well (MQW) LED structure consists of a 30 nm-thick GaN nucleation layer, a 4 μm-thick Si-doped GaN n-cladding layer, an InGaN/GaN 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 5 periods of 3 nm-thick $In_{0.23}Ga_{0.77}N$ well layers and 7 nm-thick GaN barrier layers. Surface of the samples was then partially etched until the n-type GaN layer was exposed. The n-type mesa was definition by inductively coupled plasma etcher using Cl_2/Ar as the etching gases. ITO, Ni/ITO and/or Ni/Au 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 three 2-in. sapphire substrates were then lapped down to about 90 nm. We then used scribe and break to fabricate 390 μm × 390 μm InGaN/GaN LED chips with different p-contact materials. These LED chips were then packaged into LED lamps. Room temperature electroluminescence (EL) characteristics of these fabricated LED lamps were then evaluated by injecting different amount of DC current into these LED lamps. The output power was then measured using the molded LEDs with the integrated sphere detector from top of the devices. The reliabilities of these LEDs were then evaluated by injecting a 20 mA DC current at room temperature into these devices for more than 1000 h.

3. Results and discussion

Fig. 1 shows the transmission spectra of the three different kinds of contact layers. In this figure, the transmittance of each film was normalized with respect to the transmittance of the glass substrate. Among these three contact layers, it can be seen that ITO has the largest transmittance while Ni/Au has the smallest transmittance. It can be seen from Fig. 1 that the measured transmittance at 470 nm was 71.7%, 86.6% and 98.2% for Ni/Au, Ni/ITO and ITO contact, respectively. Compared to Ni(3.5 nm)/ITO(60 nm) contact, the smaller transmittance observed from Ni(5 nm)/Au(5 nm) contact could be attributed to the larger Ni layer thickness and the more opaque nature of Au layer. On

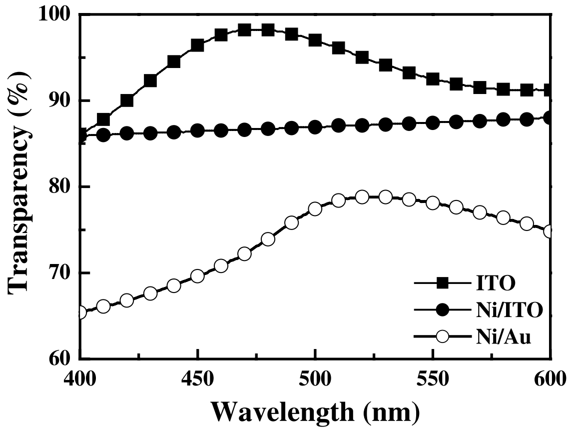

Fig. 1. Transmission spectra of Ni(5 nm)/Au(5 nm), Ni(3.5 nm)/ITO(60 nm) and ITO (60 nm) films.

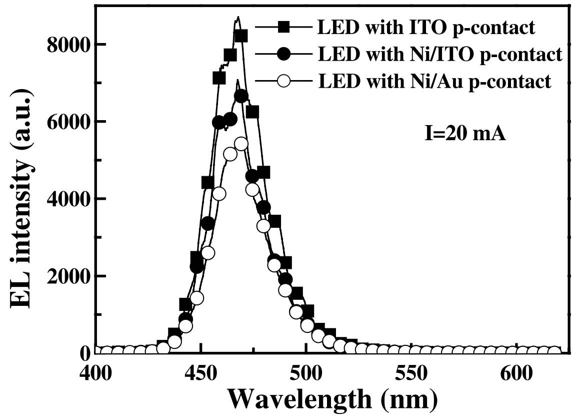

Fig. 3. Twenty milliampere EL spectra of nitride-based LEDs with Ni/Au, Ni/ITO and ITO p-contacts.

the other hand, the high 98.2% transmittance observed from ITO contact suggests ITO is indeed suitable optically to serve as the upper p-contact for nitride-based LEDs. However, the electrical properties of contact layers are also important. Fig. 2 shows the *I–V* characteristics of Ni/Au, Ni/ITO and ITO contacts on p-GaN. It was found that we would achieve a non-ohmic contact with a rectifying property when we deposited ITO directly onto p-GaN. However, we could change such a rectifying contact into ohmic with a specific contact resistance of $1 \times 10^{-3}\ \Omega\,\mathrm{cm}^2$ by inserting a thin 3 nm Ni layer in between ITO and p-GaN. It was also found that Ni/Au could form an even better ohmic contact on p-GaN with a specific contact resistance of 5×10^{-4} $\Omega\,\mathrm{cm}^2$, as shown in Fig. 2. Such a result suggests that although the transmittance of ITO film is high, it is not suitable to be used as the p-contact material of nitride-based LEDs due to the poor *I–V* characteristics observed from ITO on p-GaN. On the other hand, although the specific contact resistance of Ni/ITO on p-GaN is two times larger than Ni/Au on p-GaN, Ni/ITO is still electrically usable as the ohmic contact material for p-GaN.

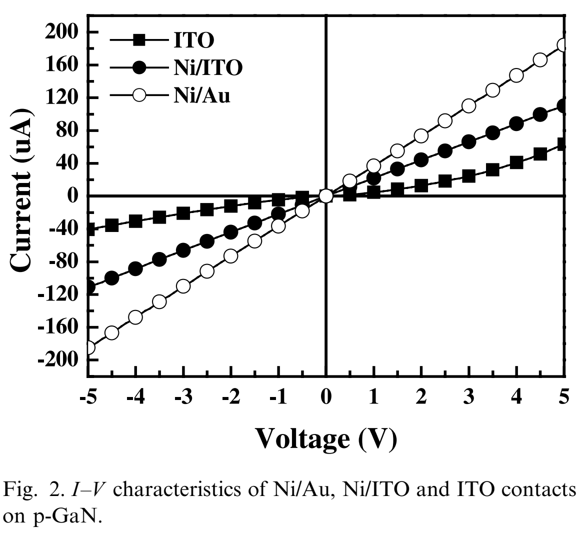

Fig. 2. *I–V* characteristics of Ni/Au, Ni/ITO and ITO contacts on p-GaN.

Fig. 3 shows the 20 mA EL spectra of the three different kinds of LEDs. It can be seen that although the EL peak positions of these three LEDs were about the same, the LED with ITO p-contact layer had the largest EL intensity while the LED with Ni/Au p-contact layer had the smallest EL intensity. Such an observation agrees well with the result shown in Fig. 1 and could be attributed to the difference in transparency of the three different p-contact materials. Fig. 4 shows the measured forward voltage and EL intensity as functions of injection current of nitride-based LEDs with Ni/Au, Ni/ITO and ITO p-contacts. It can be seen clearly from the *L–I–V* characteristics that the LED forward voltage measured with a 20 mA current injection was 3.65, 3.26 and 3.24 V for the LEDs with ITO, Ni/ITO and Ni/Au p-contact layer, respectively. The much larger 3.65 V forward voltage observed from the LED with ITO p-contact could again be attributed to the poor *I–V* characteristics observed from ITO on p-GaN. It is also interesting to compare LEDs with Ni/ITO and Ni/Au p-contacts. Although the measured specific contact resistance was two times larger for the LED with Ni/ITO p-contact, the 3.26 V forward voltage observed from the LED with Ni/ITO p-contact was only slightly larger than the 3.24 V forward voltage observed from the LED with Ni/Au p-contact. Such a result again suggests that Ni/ITO is electrically usable as the ohmic contact material for p-GaN.

As also shown in Fig. 4, the measured output power was 7.50, 6.59 and 5.26 mW for the LEDs with ITO, Ni/ITO and Ni/Au p-contact layer, respectively. Although

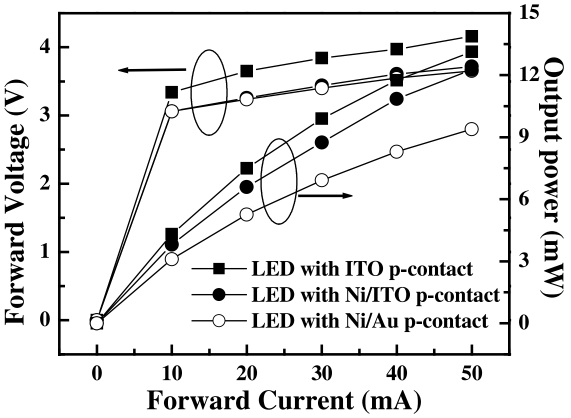

Fig. 4. Measured forward voltage and EL intensity as functions of injection current of nitride-based LEDs with Ni/Au, Ni/ITO and ITO p-contacts.

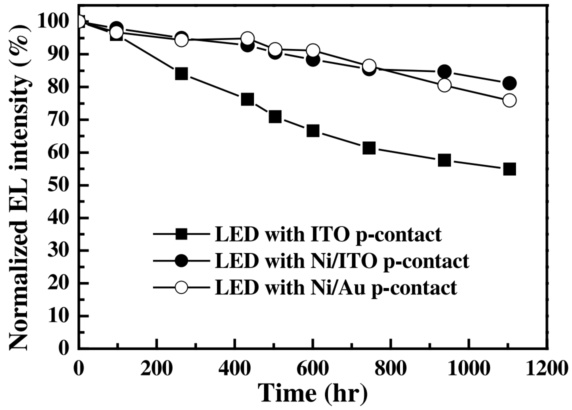

Fig. 6. Room temperature life test of relative luminous intensity measured from these three LEDs, normalized to their respective initial readings.

the LED with ITO p-contact has the largest output power under low current injection, its EL intensity decreases significantly under high current injection. Fig. 5 shows the *L–I* characteristics of the three LEDs under high current injection. It can be seen that the EL intensity of LED with ITO p-contact starts to decrease when the injection current is larger than 220 mA. In contrast, the peak EL intensity occurred at 260 mA for the LEDs with Ni/ITO and Nu/Au p-contacts. Since the operation voltage was much higher for the LED with ITO p-contact, a large amount of heat should be generated at the ITO/p-GaN interface. As a result, the output intensity degradation will occur at an earlier stage, as compared to LEDs with Ni/ITO and Nu/Au p-contacts. Such a thermal effect will also have a significant impact on the reliability of these LEDs. Fig. 6 shows room temperature life test of relative luminous intensity measured from these three LEDs, normalized to their respective initial readings. During life test, all three LEDs were driven by a DC 20 mA current injection. It was found that the luminous intensity decayed by less than 20% after 1100 h for the LEDs with Ni/ITO and Ni/Au p-contacts. In contrast, the luminous intensity decayed by 45% after 1100 h for the LED with ITO contact. Such a result is again due to the poor *I–V* characteristics observed from ITO on p-GaN. Thus, LED with ITO p-contact will have a severe heating effect especially under high current injection. As a result, the lifetime of LED with ITO p-contact is much shorter, as can be seen from Fig. 6.

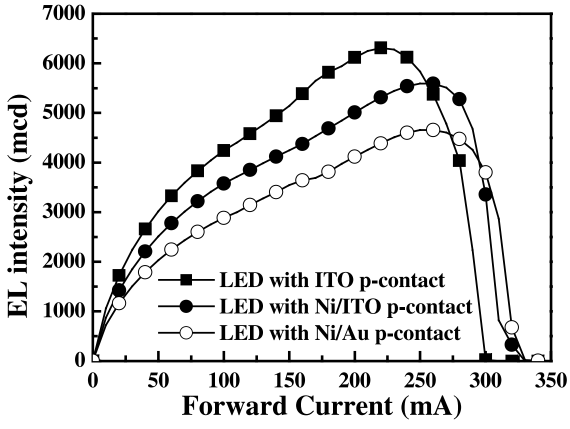

Fig. 5. *L–I* characteristics of nitride-based LEDs with Ni/Au, Ni/ITO and ITO p-contacts under high current injection.

4. Summary

In summary, we have deposited Ni(5 nm)/Au(5 nm), Ni(3.5 nm)/ITO(60 nm) and ITO (60 nm) films onto both glass substrates and p-GaN epitaxial layers. It was found that the normalized transmittance of ITO and Ni/ITO films could reach 98.2% and 86.6% at 470 nm, which was much larger than that of the Ni/Au film. It was also found that both Ni/ITO and Ni/Au could form good ohmic contact on top of p-GaN. In contrast, ITO on p-GaN was electrically poor and non-ohmic. Nitride-based LEDs with these three p-contact layers were also fabricated. It was found that the LED forward voltage was 3.65, 3.26 and 3.24 V for the LEDs with ITO, Ni/ITO and Ni/Au p-contact layer, respectively. With a 20 mA current injection, it was also found that measured output power was 7.50, 6.59 and 5.26 mW for the LEDs with ITO, Ni/ITO and Ni/Au p-contact layer, respectively. Although the LED with ITO p-contact could provide the largest output EL intensity, its lifetime was the shortest due to severe heating effect.

Acknowledgements

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