Improvement of the light output and contact resistance of InGaN-based light-emitting diodes based on tantalum-doped indium tin oxide as p-type electrodes*

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This paper reports that highly transparent and low resistance tantalum-doped indium tin oxide (Ta-doped ITO) films contacted to p-type GaN have been prepared by the electron-beam evaporation technique. The Ta-doped ITO contacts become Ohmic with a specific contact resistance of $\sim 5.65 \times 10^{-5}$ Ω·cm^2 and show the transmittance of ∼98% at a wavelength of 440 nm when annealed at 500 °C. Blue light emitting diodes (LEDs) fabricated with Ta-doped ITO p-type Ohmic contact layers give a forward-bias voltage of 3.21 V at an injection current of 20 mA. It further shows that the output power of LEDs with Ta-doped ITO contacts is enhanced 62% at 20 mA in comparison with that of LEDs with conventional Ni/Au contacts.

Keywords: p–GaN, tantalum-doped indium tin oxide (Ta-doped ITO), Ohmic contact, specific contact resistance

PACC: 7280E, 7340C, 6170T

1. Introduction

Group III-nitride semiconductors are of great importance for their applications in optoelectronic devices, such as backlighting units for liquid-crystal displays, car interiors, and solid-state lighting.[1] In the rapid progress of III–V nitride semiconductor devices, one major concern is the development of low-resistance metal contacts to p–GaN semiconductors to substantially improve the efficiency and reliability of GaN-based electrical and optical devices. Since Ho *et al.*[2] found that very-low-resistance Ohmic contact to p–GaN could be achieved by oxidization of Ni/Au contact, this contact scheme has been widely adopted.[3−5] However, it was also shown that the transmittance of semi-transparent Ni/Au films for blue light emitting diodes (LEDs) is only about 60%–85% in the 450–550 nm wavelengths by Sheu *et al.*[6] Masaaki Suzuki *et al.* reported that bilayered Ta/Ti contacts have a value of around 3×10^{-5} $\Omega \cdot \mathrm{cm}^2$ for p-type GaN. But the electrical deterioration of the Ohmic contact is terrible.[7] In order to reduce the absorption of the semi-transparent film, it is feasible to replace the conventional Ni/Au contact by a more transparent conductive material. Nowadays transparent conductive oxide materials, such as indium–tin-oxide (ITO), aluminium-doped–zinc-oxide, cadmium–tin-oxide, gallium-doped–zinc-oxide and copper-doped–indium-oxide are widely applied to optical electronic devices.[8−12] There is also some research[13−19] which discussed the applications of ITO to GaN-based LEDs. Margalith *et al.*[12] showed Schottky characteristics of the ITO/p–GaN interface after thermal annealing. This result could be attributed to a large work function difference between ITO and p–GaN. It was reported that the insertion of an Ni, NiO, ZnNi or Sn–Ag alloy layer between ITO and p–GaN was very effective in improving the electrical and optical properties of GaN based LEDs.[13−17] Chang *et al.*[18] also presented that the ITO/p–GaN interface could be a nearly Ohmic contact by inserting a thin p–$In_{0.1}Ga_{0.9}N$ layer as an intermediate layer to reduce the Schottky barrier height between ITO and p–GaN. LEDs with this kind of contact structure would have a moderately higher forward voltage but a large enhancement in external quantum efficiency and power efficiency.

A variety of different schemes have been inves-

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tigated to achieve low-resistance p-type Ohmic contacts by using various methods. In this work, we used a deposition and annealing technique (DA technique) to investigate a multi-TCO scheme to form low resistance and transparent p-type Ohmic contacts. We selected the transition metal of tantalum as dopants into ITO, because these metals were reported to have negative enthalpies for hydride formation smaller than that needed to form hydrides with Mg atoms.[20] The ITO ($In_2O_3/SnO_2 = 95/5$ wt.%) source contains 0.2 wt.% tantalum. We first compared their contact resistances and transmittances with the annealed Ta-doped ITO, ITO, and oxidized Ni/Au contacts. The Ta-doped ITO was annealed at 400, 500, and 600 °C for 30 min in O_2 ambience, respectively. Then, we compared the electrical characteristics and the current-light output power behaviours of InGaN/GaN multiple-quantum-well LEDs with Ta-doped ITO, ITO and conventional Ni/Au as the p-type Ohmic contacts.

2. Experiments

The p–GaN layers (0.7 μm thick, 4×10^{17} cm^{-3}) were grown on a sapphire substrate by using a metal-organic chemical-vapour deposition system supplied by Aixtron Co. During the growth, trimethylgallium, trimethylindium, trimethylaluminium, 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. The specific contact resistance was measured by using circular transmission line method (c-TLM) patterns, which were formed by photolithography and lift-off techniques. The inner dot radius was 50 μm and the spacing between the inner and the outer radii varied from 5 μm to 30 μm. Prior to metal deposition, all the samples were treated in a diluted HCl solution for 1 min, and the Ta-doped ITO layers were deposited by electron beam-evaporation. The thickness of Ta-doped ITO was fixed at 250 nm in this experiment, and they were annealed by a thermal process at temperatures of 400, 500, and 600 °C for 30 min in O_2 ambience to make the Ohmic contacts. All of the samples were deposited by using an electron-beam evaporator and subsequently annealed at various conditions. The current–voltage (I–V) characteristics of samples and InGaN/GaN blue LEDs were investigated using a Keithley 4200 semiconductor parameter analyser.

3. Results and discussions

Figure 1 shows the I–V curves of the annealed Ta-doped ITO, ITO, and oxidized Ni/Au samples. The as-deposited Ta-doped ITO contacts produced nonlinear I–V characteristics (not shown). However, the electrical properties of the samples are considerably improved upon annealing at a temperature in the range of 400–600 °C. As for the ITO contact, its I–V curve still shows a nonlinear characteristic even after annealing. Specific contact resistance was determined from the plots of the measured resistances versus the spacing between the c-TLM pads. Measurements showed that the specific contact resistance of Ta-doped ITO contact is 5.65×10^{-5} $\Omega \cdot$cm^2 when annealed at 500 °C, which is lower than that (1.04×10^{-4} $\Omega \cdot$cm^2) of the most commonly used Ni/Au contacts. The finding that the electrical properties of the annealed Ta-doped ITO samples are much better than those of the annealed ITO contact indicates that the tantalum element which is doped into ITO plays an important role in lowering contact resistance.

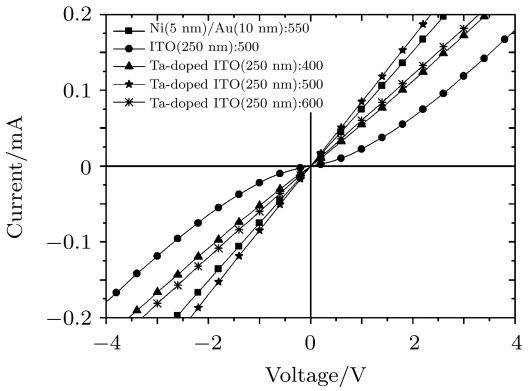


Fig. 1. The I–V characteristics of the annealed Ta-doped ITO contacts, which are compared with those of Ni/Au and ITO contacts.

It is interesting that the electrode Ta-doped ITO showed a low specific contact resistance without insertion of Ni, NiO or Ni/Au. This low contact resistance is likely the result of doping the tantalum element into ITO. That is, Ta was added since it would be expected to form hydrides which are beneficial to the formation of p-type Ohmic contacts. During the annealing process of the Ta-doped ITO electrodes on p-type GaN, the Mg–H bond complex in p–GaN may be broken and the hydrogen atoms that become detached from the bond complex may form hydrides with tantalum atoms. Because tantalum atoms have negative enthalpies for hydride formation smaller than that needed to form hydrides with Mg atoms,[20] they

are expected to facilitate out-diffusion of the H atoms from the GaN epilayer and to remove hydrogen atoms at elevated temperatures. Therefore, Ta elements can enhance the mobility of Mg-doped GaN and reduce the ionization energy of the Mg acceptor. This lowering of the ionization energy of the Mg acceptor reduces the Schottky barrier height between p–GaN and the electrode,[21] and eventually reduces the specific contact resistance.

Figure 2 shows the magnitude of the optical light transmittance for the same Ta-doped ITO, ITO and Ni/Au layers deposited on glass substrates. The Ta-doped ITO annealed at 500 °C shows higher transmittance than other electrodes which were annealed at various conditions in the range of wavelengths from 425 nm to 475 nm. This is thought to be due to the low light absorption coefficients of ITO. The high annealing treatment can cause a considerable reduction of some defects and restructuring of Ta-doped ITO crystallinity; these facts lead to improvement of the optical properties. Therefore, the transmittance of annealed Ta-doped ITO is higher than that of as-deposited Ta-doped ITO.[22] These results suggest that the Ta-doped ITO contact scheme is suitable for use as a highly transparent and low specific contact resistance contact layer for p–GaN.

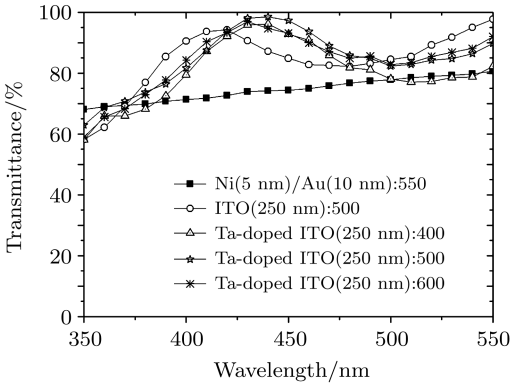


Fig. 2. Optical transmittance characteristics for the ITO contacts annealed at 500 °C, Ni/Au contacts annealed at 550 °C and Ta-doped ITO contacts annealed at 400, 500, and 600 °C, respectively.

In order to investigate if the Ta-doped ITO p-type contact layers are suitable for devices, we fabricated InGaN/GaN blue LEDs with Ta-doped ITO (250 nm) p-type Ohmic contacts, which were annealed at 400, 500, and 600 °C for 30 min in oxygen ambience shown in Fig. 3. For comparison, the I–V behaviours of LEDs made with the annealed ITO and Ni/Au p-type Ohmic contact layers were also characterized. The LEDs with the annealed Ta-doped ITO contact layer give a forward-bias voltage of ∼3.21 V at an injection current of 20 mA, which is somewhat better than that of the LEDs with the oxidized Ni/Au contact layers. However, the LEDs fabricated with the annealed ITO contacts show a high forward voltage (∼3.90 V). The inset of Fig. 3 shows the electroluminescence (EL) spectra of the LED with Ta-doped ITO contact layer annealed at 500 °C at 20 mA. A pure blue emission with an emitting wavelength around 450 nm where the transmittance of Ta-doped ITO is higher than 90% was observed; this fact implies that the device has a high optical quality.

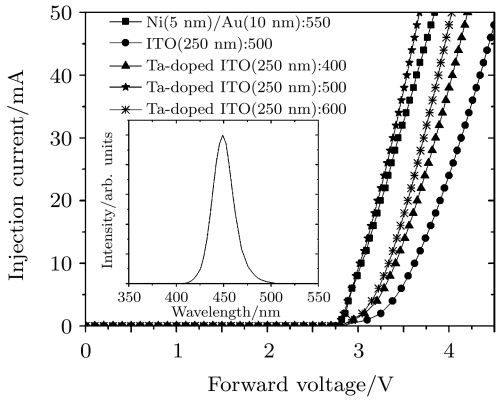


Fig. 3. The electrical characteristics of InGaN/GaN blue LEDs fabricated with the annealed Ta-doped ITO, ITO, and oxidized Ni/Au contacts. Inset shows EL spectra of the LED with Ta-doped ITO contact layer annealed at 500 °C at the injection current of 20 mA.

Figure 4 shows the current–light output powers of the LEDs made with the annealed Ta-doped ITO, ITO and oxidized Ni/Au contacts. It is shown that the light output power of the LEDs with the Ta-doped ITO contacts is much better than that with the ITO

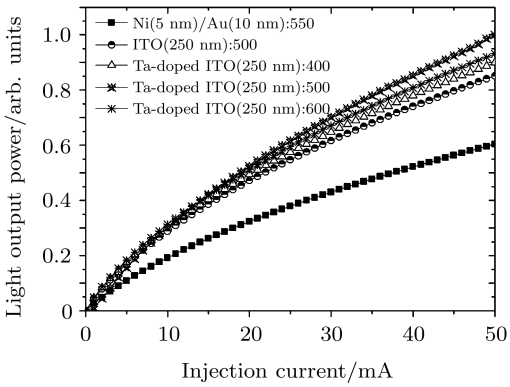


Fig. 4. The current–light output power behaviours of InGaN/GaN blue LEDs fabricated with the annealed Ta-doped ITO, ITO, and oxidized Ni/Au contacts.

and Ni/Au contacts. In other words, for the LEDs with the Ta-doped ITO contact layers, the output

power at 20 mA is enhanced 62% in comparison with that of the LEDs with the Ni/Au contact layers. This is consistent with the combined results of their contact resistances and optical transmittances (Figs. 1 and 2).

4. Conclusion

In summary, we used Ta-doped ITO electrodes to make highly transparent and low-resistance Ohmic contacts on p-type GaN. The Ta-doped ITO electrodes give specific contact resistance as low as $5.65 \times 10^{-5}\ \Omega \cdot \mathrm{cm}^2$ and light transmittance higher than 98% at 440 nm when annealed at 500 °C for 30 min in oxygen ambience. It is further shown that the LEDs fabricated with annealed Ta-doped ITO p-type contact layers give much better light output power in comparison with that of LEDs with oxidized Ni/Au contacts. The results indicate that the annealed Ta-doped ITO scheme could serve as a highly promising Ohmic electrode for the fabrication of high-brightness top-emitting LEDs.

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