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Transparent Phosphorus Doped ZnO Ohmic Contact to GaN Based LED

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Abstract This study develops a highly transparent ohmic contact using phosphorus doped ZnO with current spreading for p-GaN to increase the optical output power of nitride-based light-emitting diodes (LEDs). The phosphorus doped ZnO transparent ohmic contact layer was prepared by radio frequency magnetron sputtering with post-deposition annealing. The transmittance of the phosphorus doped ZnO exceeds 90% in the region of 440 nm to 500 nm. The specific contact resistance of the phosphorus doped ZnO on p-GaN was determined to be 7.82×10^{-3} Ω·cm^2 after annealing at 700 °C. GaN LED chips with dimensions of 300×300 μm fabricated with the phosphorus doped ZnO transparent ohmic contact were developed and produced a 2.7 V increase in forward voltage under a nominal forward current of 20 mA compared to GaN LED with Ni/Au Ohmic contact. However, the output power increased by 25% at the injection current of 20 mA compared to GaN LED with the Ni/Au contact scheme.

Key words phosphorus doped ZnO, ohmic contact, GaN LED.

1. Introduction

GaN and related compounds are attractive materials for optoelectronic devices in the blue and ultraviolet spectral region.[1-3] However, low contact resistance and low transmission efficiency reduce the overall performance of these electronic and optical devices. Especially, the fabrication of high-quality ohmic contacts with low resistance, thermal stability, and high transparency, is of great technological importance for the optical device applications. Currently, it is hard to grow heavily doped p-GaN (>10^{18} cm^{-3}) and there is no appropriate metal with a work function larger than that of GaN (~7.5 eV). Thus, oxidizing Ni/Au thin film is commonly used as the ohmic contact to p-GaN.[4,5] The main concept is to use p-NiO with nickel vacancies and/or oxygen interstitials contacts to p-GaN to reduce interface resistance. However, the Au-based contacts generally have poor thermal stability, leading to poor device reliability. Recently, Ni/ITO thin film shows the low resistance and transparent ohmic contact to p-GaN.[6]

In other hands, ZnO, an optically transparent material, is widely used in various applications, including light-emitting diodes (LED), flat-panel displays, and solar cells. Recently, we reported on the successful growth of phosphorus doped p-ZnO with a high hole concentration (>10^{18} cm^{-3}).[7,8] The phosphorus doped ZnO can be used as the transparent ohmic contact layer due to its high carrier concentration and high transparency. In this study, we report on the development of GaN LED chips with a phosphorus doped p-ZnO transparent ohmic contact.

2. Experimental Procedure

The MQW samples were grown on c-plane sapphire substrates using metallorganic vapor deposition in a rotating disk reactor (Emcore D125). The LED structures consisted of a GaN nucleation layer, a Si-doped n-GaN layer, five periods of InGaN/GaN MQW active layer, and a Mg-doped p-GaN capping layer. A detailed description of the growth procedures was provided elsewhere.[9] To investigate the effect of a phosphorus doped ZnO transparent ohmic contact layer on electrical and optical performance of LEDs, two types of LED chips each with an area of 300×300 μm were fabricated as follows. The surface of the p-type GaN layer was partially etched using an inductively coupled $CH_4/Cl_2/H_2/Ar$ plasma until the n-GaN layer was exposed. A Ti/Al (30 nm/80 nm) film was deposited on the n-type GaN layer via e-beam evaporation, and a Ni/Au film of 3 nm/8 nm in thickness by e-beam evaporation and a phophorus doped ZnO of 250 nm in thickness by radio frequency sputtering, respectively, were deposited

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onto the p-GaN layer as the current spreading layer.[7] Finally, Ni/Au (30 nm/80 nm) was subsequently evaporated on the current spreading layer as the top electrode. These metals were patterned by a standard metal lift-off technique. Prior to the metal deposition, the samples were cleaned in a buffered oxide etchant (BOE) solution. This step was found to greatly enhance the adhesion of metal layers by removing oxides from the surfaces of the exposed GaN. All metal contacts were annealed at 500 ^{o}C for 30 s under a N_2 gas ambient. A phophorus doped ZnO was annealed at 600 ^{o}C for 1min under a N_2 gas ambient. For the electrical and optical characteristics of the MQW LED, the current-voltage (I-V) and the electroluminescence (EL) measurements were performed at room temperature. The inner dot radius was 200 μm and the spacing between the inner and the outer radii varied from 5 to 50 μm. To characterize the extent of inter-diffusion between the p-ZnO layer and the p-GaN film, Auger electron spectroscopy (AES) analysis was performed using a PHI 670 Auger microscope with an electron beam energy of 10 keV and a current of 0.029 μA. X-ray photoemission spectroscopy (XPS) was carried out using an Al $K\alpha$ X-ray source in XPS system (PHI 5200 model).

3. Results and discussions

Fig. 1(a) shows the current-voltage (*I–V*) characteristics of the p-ZnO contact layers on p-GaN, measured between ohmic pads with a spacing of 50 μm. The p-ZnO contact shows good ohmic contact to p-GaN after the annealing at 700 ^{o}C for 1 min under a nitrogen ambient. Even though ZnO : P annealed at 900 ^{o}C shows highest electrical properties (hole concentration and mobility),[7] the contact property degraded after the annealing at 900 ^{o}C for 1 min under a nitrogen ambient. This might be attributed to the oxygen in-diffusion in to p-GaN to form gallium oxide at the interface. When surface oxides exist on p-GaN, holes in valence band are trapping into deep levels in the oxides because surface oxides have a number of defects. The p-ZnO contact exhibited a linear ohmic behavior in the voltage range of $-2 \sim 2$ V. The specific contact resistance was calculated from plots of the measured resistances versus the spacings between the c-TLM pads. The specific contact resistance was determined to be $7.82 \times 10^{-3}\Omega\cdot cm^2$ after the annealing at 700 ^{o}C, indicating that the p-ZnO can be used as a good ohmic scheme for p-GaN. The light transmittance of the annealed p-ZnO was measured and the values were found to be above 90% in the region of 440 nm to 500 nm due to the large bandgap of ZnO (3.3eV at room temparature).[10] The reason why we adopted a nitrogen ambient was that during the annealing process, phosphorus oxide supplies two phosphorus atoms acting as acceptors and five oxygen atoms which may compensate oxygen vacancies that act as donors.[7]

In-depth Auger profiles of the p-ZnO contact layers on p-GaN before and after the annealing process are shown in Fig. 2. Almost no reaction occurred at the interface between GaN and ZnO after the annealing comparing to the as-deposited p-ZnO on p-GaN. It indicates that deep levels to trap holes at the interface are not formed by the diffusion.

To characterize the chemical bonding state of P and O atoms in p-ZnO ohmic schemes, XPS analysis was performed on the ohmic contact layers on the p-GaN, after annealing in a nitrogen ambient. P 2*p* core-level peak observed

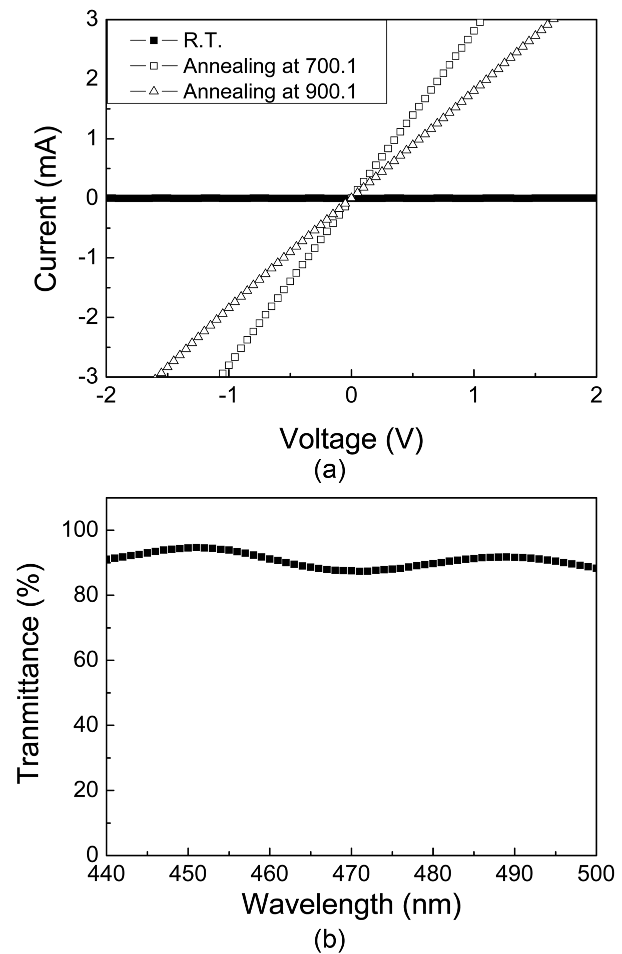

Fig. 1. (a) I-V characteristics of the p-ZnO contacts to *p*-GaN before and after different annealing processes. (b) The light transmittance for a p-ZnO sample annealed at 700 ^{o}C for 1min.

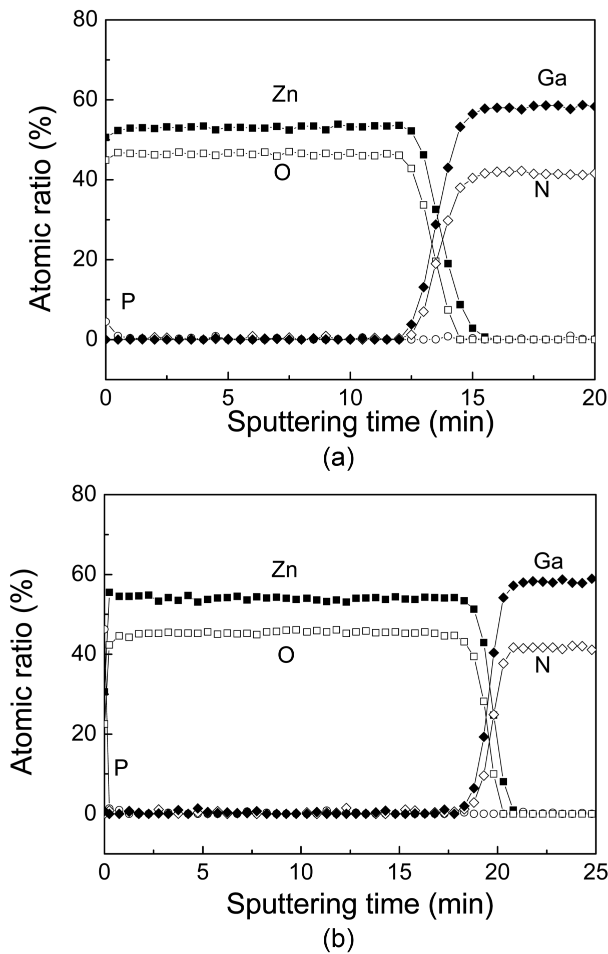

Fig. 2. AES depth profiles of p-ZnO contacts to *p*-GaN before and after annealing at 700 °C for 1min under a nitrogen ambient.

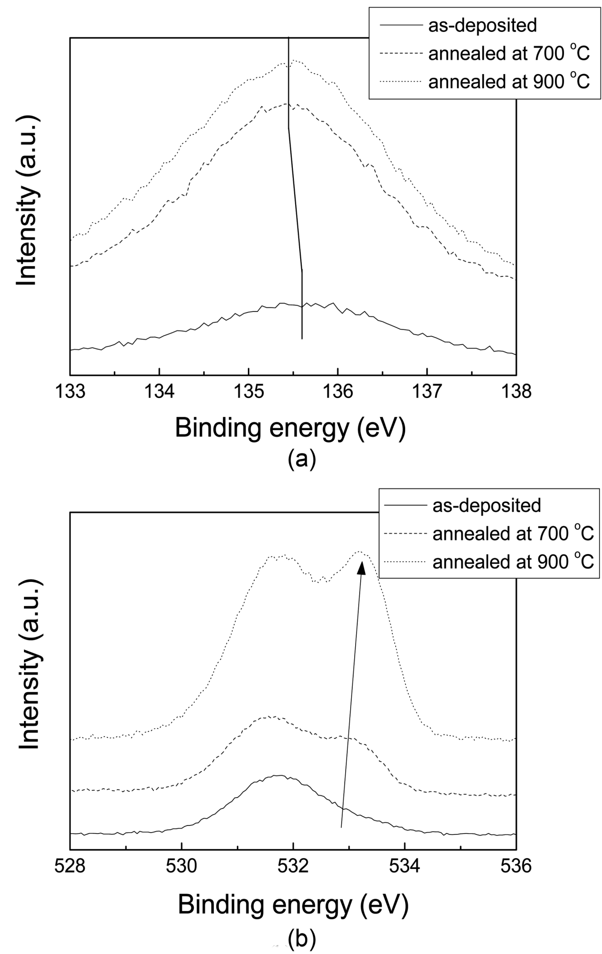

Fig. 3. (a) P 2*p* core level peaks and (b) O 1*s* core level peaks observed at the interface of p-ZnO/p-GaN before and after different annealing processes under a nitrogen ambient.

at a binding energy of 135.6 eV is believed to come from P_2O_5 in the thin film. P 2*p* core level peak regarding pure phosphorus state is normally observed at a binding energy of 130 eV.[11] As the annealing temperature increases, P 2*p* core-level peak is shifted to the lower energy level which indicates that P and O atoms exchange the sites, resulting in the activation of P atoms for acceptors. O 1*s* core-level peak at high energy side increased as annealing temperature increased. This result shows that the amount of loosely bound oxygen increased, which can compensate the formation of oxygen vacancies in ZnO during the annealing process. This is the mechanism for the activation of p-ZnO : P.[7]

To verify the increase in hole injection and current spreading by using IZO-based contact schemes, we fabricated LEDs with a dimension of 300×300 μm^2. Fig. 3 shows the I-V characteristics of LEDs with different *p*-ohmic contacts. It can be seen that the forward voltage measured at an injection current of 20 mA was 3.6 V and 5.9 V for Ni/Au and p-ZnO contacts to *p*-GaN, respectively. It is noteworthy that the forward voltage of the LED with a p-ZnO ohmic layer was increased by 2.3 V compared to that of LEDs with standard Ni/Au contacts. The series resistances of the LED with Ni/Au and p-ZnO contacts are 25.5 and 35.6 Ω, respectively. Even though the specific contact resistance of the annealed p-ZnO contact is slightly higher than that of the Ni/Au contact, the high forward voltage of GaN LED with p-ZnO contact can be attributed to the high sheet resistance of p-ZnO film and oxide formation on p-GaN due to Ar ion bombardment effect during the deposition of p-ZnO.

In Fig. 4 the electroluminescence (EL) spectrums of LEDs prepared using the two different ohmic schemes, Ni/Au and p-ZnO, were shown with the injection current of 20 mA to make the same recombination of holes and electrons. The EL peak positions of both LEDs are the same of

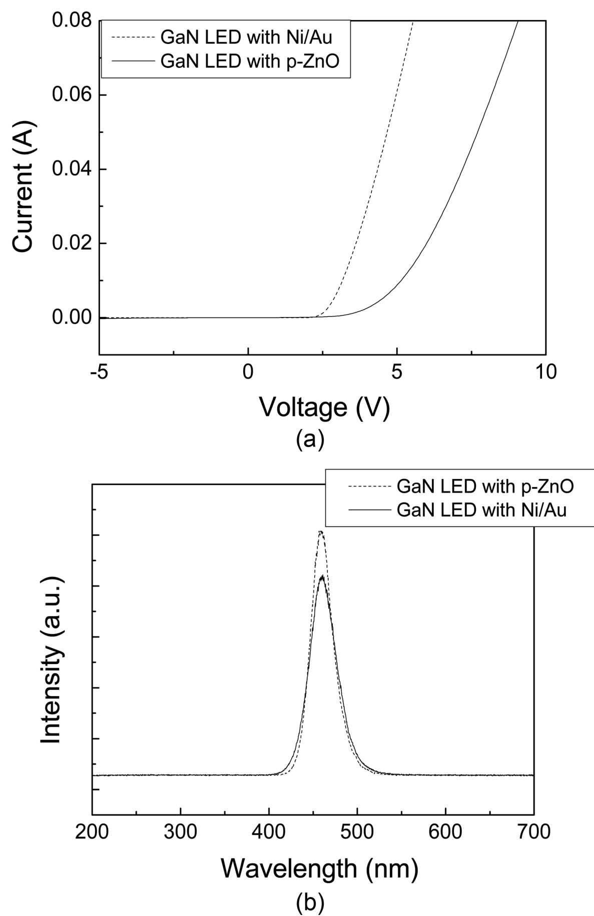

Fig. 4. (a) I-V curves and (b) EL spectrums of LEDs with conventional Ni/Au and transparent p-ZnO ohmic contacts.

460 nm. The light output power for LED with p-ZnO film was increased by 25.0% at 20 mA compared to that with Ni/Au metal film. The light output powers are compared at the same injection current because the same recombination rate is achieved at the same injection current, resulting in the same amount of light generation in the devices. The light transmittances of the annealed Ni/Au and p-ZnO are 70.2 and 91.2%, respectively.[13] The transmittance of p-ZnO is 29.9% higher than that of Ni/Au, which is a little higher than the increase of output power, 25.0%. This can be attributed that the higher voltage on GaN LED with p-ZnO might induce heating which can deteriorate the internal efficiency. The enhancement of light output power, however, could be attributed to the high light transmittance of the annealed p-ZnO film compared to that of the Ni/Au layer.

4. Conclusions

In summary, p-ZnO ohmic scheme was investigated as highly transparent and ohmic contacts to p-GaN. The p-ZnO contact, after annealing at 700 ^{o}C for 1min in a nitrogen ambient, produced a low specific contact resistance of $7.82 \times 10^{-3}\,\Omega\cdot cm^2$. The forward voltage and series resistance of GaN LED with p-ZnO increased possibly due to the poor current spreading and/or oxide formation during the deposition of p-ZnO. However, the light output power for LED with p-ZnO film was increased by 25% at 20 mA compared to that with Ni/Au metal film. This is attributed to the high transmittance of p-ZnO film.

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