P-7-7

Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp230-231

# An *n*-ZnO/*p*-GaN Ultraviolet Light Emitting Diode Prepared Using Radio-Frequency Magnetron Cosputtering System

Nan-Jay Wu[1], Chen-Peng Hsu[2], Yao-Jun Tsai[2], Bo-Ting Lai[3], and Day-Shan Liu[*1]

[1]Institute of Electro-Optical and Material Science, National Formosa University, Yunlin 63201, Taiwan
[2]Electronics and Optoelectronics Research Laboratories, Industrial Technology Research Institute, Hsinchu, 31040, Taiwan
[*]Tel: 886-5-6315665; Fax: 886-5-6329257; E-mail: dsliu@sunws.nfu.edu.tw

## 1. Introduction

Zinc oxide (ZnO) has recently attracted significant attention as an efficient material for applications in UV light emitting diodes (LEDs) [1]. However, due to the reliability of *p*-type ZnO is still under debate, researches have focused on the preparation of hetero-junction LED based on ZnO [2-3]. To engineer a ZnO-based heterojunction LED, the quality of the electrode ohmic contact to ZnO layer is critical [4]. With the aim to prepare a quality *n*-ZnO/*p*-GaN heterojunction LED, we developed a transparent conductive oxide (TCO) film cosputtered from ITO and ZnO material in substitution for the thin metals ohmic contact to *n*-type ZnO layer. The *n*-ZnO/ITO-ZnO ohmic contact structure was optimized after a rapid thermal annealed (RTA) process. The properties of the *n*-ZnO/*p*-GaN LED were investigated from the electroluminescence (EL) spectrum and the current-voltage (*I-V*) characteristic.

## 2. Experimental procedure

An unintentionally doped *n*-type ZnO layer was deposited on c-$Al_2O_3$ substrate by using the radio frequency (rf) magnetron cosputtering system and post-annealed under vacuum ambient. The ITO-ZnO cosputtered film at an atomic ratio of 33% [Zn/(Zn+In) at.%] was deposited onto the *n*-type ZnO layer by the rf magnetron cosputtering system, using ITO and ZnO targets [5]. To improve the ohmic contact behavior of the *n*-ZnO/ITO-ZnO system, an RTA process under ambient vacuum was carried out. For the heterojunction LED fabrication, Ni/Au ohmic contact electrode was firstly deposited onto the *p*-GaN layer and optimized. The *n*-ZnO/*p*-GaN heterostructure was then formed by the preparing of an unintentionally doped ZnO layer onto the Mg-doped *p*-GaN epilayer. Eventually, the cosputtered ITO-ZnO electrode was deposited onto the *n*-type ZnO layer and optimized by an RTA process. Current-voltage (*I-V*) properties of the *n*-ZnO/ITO-ZnO contact structure as well as the *n*-ZnO/*p*-GaN heterojunction LED were characterized using a semiconductor parameter analyzer. The crystalline structure of the *n*-ZnO/ITO-ZnO contact system was determined using X-ray diffraction (XRD) patterns. The interface diffusion was examined by the Auger electron spectroscopy (AES) depth profiles. The electroluminescence (EL) characteristics of the resulting *n*-ZnO/*p*-GaN heterojunction LED was observed at various injected forward currents.

## 3. Results and discussions

Figure 1(a) shows the specific contact resistance of the *n*-ZnO/ITO-ZnO structure as a function of the post-annealed temperature for 1 min under vacuum ambient (*I-V* characteristics also give in the inset figure). All the contact structures exhibited ohmic contact behavior. In addition, the specific contact resistance of the *n*-ZnO/ITO-ZnO structure was decreased with increasing the annealed temperature. A low specific contact resistance (~ $1.40 \times 10^{-5}$ $\Omega$ $cm^2$) was achieved from the sample annealed at 400°C. Figure 1(b) shows the specific contact resistance of the *n*-ZnO/ITO-ZnO structure as a function of the post-annealed time at 400°C under vacuum ambient (the I-V characteristics gives in the inset figure). It can be seen that the specific contact resistance of the *n*-ZnO/ITO-ZnO structure was further optimized to $1.91 \times 10^{-6}$ $\Omega$ $cm^2$ for the

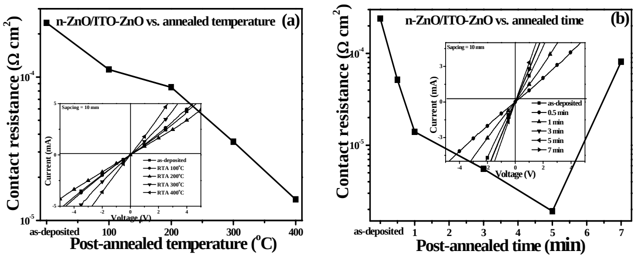



Fig. 1 Specific contact resistance of the n-ZnO/ITO-ZnO structure as a function of (a) the post-annealed temperatures and (b) the post-annealed time (the inset figures give the associated I-V characteristics).

sample annealed for 5 min, whereas an apparent increase in the specific contact resistance was obtained from the sample annealed for 7 min.

XRD and AES measurements were carried out to investigate the evolution of the *n*-ZnO/ITO-ZnO contact structure on the annealed time. Figure 2(a) shows the XRD spectra of the *n*-ZnO/ITO-ZnO contact structure processed by an RTA treatment at 400°C under vacuum ambient for 5

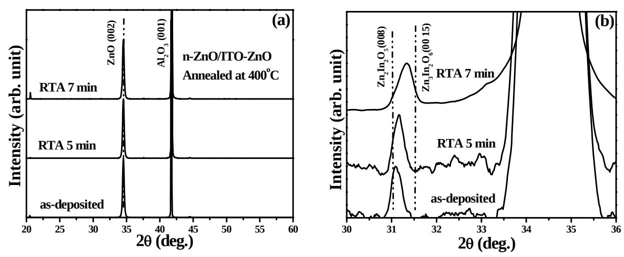
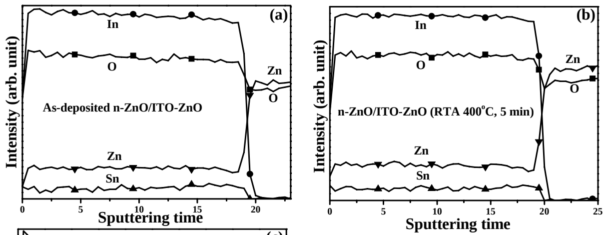



Fig. 2 (a) XRD spectra of the as-deposited n-ZnO/ITO-ZnO structure as well as the 400oC-annealed sample for 5 and 7 min, respectively and (b) High resolution XRD spectra around the 2θ values ranging from 30° to 36°

and 7 min, respectively, as well as the as-deposited sample.

Both the as-deposited and annealed samples showed *c*-axis preferred growth orientation. High resolution XRD spectra around the 2θ values ranging from 30° to 36° of Fig. 2(a) are depicted in Fig. 2(b). A weak diffraction peak related to the homologous $Zn_kIn_2O_{k+3}$ compounds was observed in



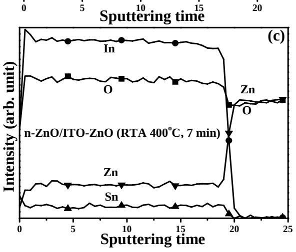




Fig. 3 AES depth profiles of the (a) as-deposited n-ZnO/ITO-ZnO structure and the 400oC-annealed samples at (b) 5min and (c) 7min, respectively.

these spectra. The diffraction peak closed the $Zn_2In_2O_5$ (008) phase in the as-deposited sample gradually shifted toward the $Zn_3In_2O_6$ (0015) phase with increasing the annealed time, indicating the evolutions of the interface diffusion. Although the interdiffusion between the interface of the ITO-ZnO and ZnO layer increased the surface concentration of the ZnO layer and thus improve the ohmic contact behavior, it would also lead the formation of defects in the interfacial layer, which resulted in the degradation of the specific contact resistance [6]. The AES depth profiles of these samples are given in Fig. 3(a)-(c). There is little difference between the depth profiles of the as-deposited and annealed *n*-ZnO/ITO-ZnO interface expect for the relative intensity of Zn/O in ZnO surface. The increase in the relative intensity of the 400$^o$C-annealed sample for 5 min (Fig. 3(b)) implied the incremental numbers of the oxygen vacancies in the ZnO surface, which corresponded to a high carrier concentration, thereby resulting in the lowest specific contact resistance.

*I-V* characteristics of the resulting n-ZnO/p-GaN heterojunction LED employs the cosputtered ITO-ZnO transparent ohmic contact electrode is shown in Fig. 4. The device exhibited the rectifying behavior with a threshold voltage of 3.9 V and leakage current of $9 \times 10^{-6}$ A as determined in the inset figure. Figure 5 shows the light-current *(L-I)* characteristics of *n*-ZnO/*p*-GaN

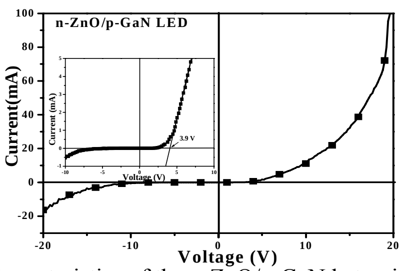



Fig. 4 I-V characteristics of the n-ZnO/p-GaN heterojunction LED.

heterojunction LED (The EL spectra as a function of the injected forward current also show in the inset figure). The EL spectra consist of a dominated UV emission peak at 405 nm and a tail extending to visible wavelength. The *L-I* curve shows a superlinear dependence at low current (< 30 mA) with a slope of 1.9 ($L \sim I^m$) and become sublinear (m=0.36) at high current (< 60 mA). The EL intensity decreased significantly as the forward current reached 70 mA due to the heating effects and series resistance [7].

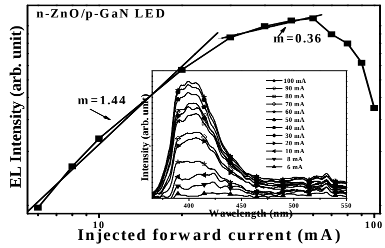



Fig. 5 L-I characteristics of the n-ZnO/p-GaN heterojunction LED (EL spectra as a function of the injected forward current show in the inset figure).

## 4. Conclusions

The ohmic contact of the cosputtered ITO-ZnO transparent electrode to the *n*-type ZnO layer was optimized with a specific contact resistance of $1.91 \times 10^{-6}$ $\Omega cm^2$ after annealing at 400°C for 5 min under vacuum ambient. The mechanism responsible for the evolutions on ohmic contact behavior was attributed to the appearance of the homologous $Zn_kIn_2O_{k+3}$ compounds at the *n*-ZnO/ITO-ZnO interface diffusion as well as the increase of the carrier concentration on the ZnO surface due to the incremental oxygen vacancies. The resulting *n*-ZnO/*p*-GaN heterojunction LED employed the cosputtered ITO-ZnO transparent electrode exhibited the rectifying behavior with the UV emission peak at 405 nm.


## Acknowledgements

This work was supported by the Industrial Technology Research Institute under no. 03-1001-014.


## References


[1] Ya. I. Alivova, J. E. Van Nostrand, D. C. Look, M. V. Chukichev, and B. M. Ataev, Appl. Phys. Lett. **83** (2008) 2943.

[2] R. W. Chung, R. X. Wu, L. W. Lai, and C. T. Lee, Appl. Phys. Lett. **91** (2007) 231113.

[3] L. Zhao, C. S. Xu, Y. X. Liu, C. L. Shao, X. H. Li, and Y. C. Liu, Appl. Phys. B **92** (2008) 185.

[4] K. Ip, Y. W. Heo, K. H. Baik, D. P. Norton, S. J. Peartona, and F. Ren, Appl. Phys. Lett. **84** (2004) 544.

[5] D. S. Liu, C. H. Lin, B. W. Huang, and C. C. Wu, Jpn. J. Appl. Phys. **45** (2006) 3526.

[6] G. Hu, B. Kumar, H. Gong, E. F. Chor, and P. Wu, Apple. Phys. Lett. **88** (2006) 101901.

[7] B. M. Ataev, Ya. I. Alivov, V. A. Nikitenko, M. V. Chukichev, V. V. Mamedov, and S. Sh. Makhmudov, J. Optoelectron. Adv. Mater. **5** (2003) 899.