Electroluminescence from ZnMgO/ZnO Heterojunctions*

Minoru Yamada, Junya Mimura, Takao Komiyama, Hiroyuki Yamaguchi, Yasunori Chonan, and Takashi Aoyama†

Department of electronics and Information Systems, Akita Prefectural University,

84-4 Ebinokuchi, Tsuchiya Yuri-honjo, Akita 015-0055, Japan

(Received 3 June 2008; Accepted 29 October 2008; Published 4 April 2009)

The p -type $\text{Zn}_{0.8}\text{Mg}_{0.2}\text{O}/n$ -type ZnO heterojunctions have been fabricated by a pulsed laser deposition (PLD) technique and the relations between the I-V and the electroluminescence (EL) characteristics were investigated. The ZnMgO film shows the best p -type characteristic for the 10% Sb concentration. The different Ga concentrations in n -type ZnO layers show different I-V and EL characteristics for the ZnMgO/ZnO heterojunctions. The 0.1% of Ga in the ZnO film shows the lowest resistivity (0.048 ohm-cm) and the highest electron mobility (59 cm^2/Vs), however, the ZnMgO/ZnO junction shows only an Ohmic contact and no EL is observed. The heterostructure using the ZnO layer with 5.0% Ga shows the best rectifying behavior, however, no EL is observed. The 1.0% of Ga in the ZnO film shows the middle resistivity (0.51 ohm-cm) and the middle electron mobility (27 cm^2/Vs) and the ZnMgO/ZnO heterojunction shows only a weak rectifying behavior but clear EL is observed. The threshold voltage of the EL is about 10V and the EL intensity is increased with the forward biases up to 20 V. These results indicate that the EL from ZnMgO/ZnO junctions does not necessarily require good ideality factors of the diodes. [DOI: 10.1380/ejsnt.2009.366]

Keywords: Electroluminescence; ZnO; ZnMgO; Heterojunction; I-V characteristic

I. INTRODUCTION

Zinc oxide (ZnO) is one of the most useful materials for the optoelectronics devices such as ultraviolet (UV) laser diodes (LD), light emitting diodes (LED) and photo detectors. Because of a lot of defects in the film, it is still a difficult task to obtain stable p -type ZnO materials. Instead of ZnO homojunctions, heterostructures of n -type ZnO with other p -type materials have been actively investigated. In the n -ZnO/ p -GaN heterojunctions fabricated by molecular beam epitaxy (MBE) and chemical vapor deposition (CVD) techniques [1], the 3V threshold voltages and the 430 nm electroluminescence (EL) were observed, however, the EL was from the p -GaN region and the expected 390 nm from the n -ZnO region was not observed. In the n -ZnO/ p -AlGaIn structures fabricated by hydride vapor phase epitaxy and CVD techniques [2], the 389 nm EL was observed from the n -ZnO region. In the same n -ZnO/ p -GaN heterostructures fabricated by metal organic vapor phase epitaxy (MOVPE) and pulsed laser deposition (PLD) techniques [3], the 375 nm EL from was observed from the n -ZnO region. In this case the carrier concentrations were in the order of 10^{17} cm^{-3} in both the n - and the p -regions. In the reverse p -ZnO/ n -GaN structures [4], the 409 nm EL was observed from the p -ZnO region. In the n -ZnO/ p -Si [5] and n -ZnO/ p -BeZnO [6] structures fabricated by the rf-magnetron sputtering and the plasma immersion ion implantation techniques, the 580 nm and 360-390 nm EL were observed from n -ZnO regions, respectively. In the n -ZnO/ p -SiC structures fabricated by the filtered arc vacuum technique [7], the 385 nm EL was observed from the ZnO region.

Because the bandgap energies of ZnMgO films can be easily controlled by changing Mg concentrations, p -type ZnMgO films have also been actively investigated. Yang

FIG. 1: Schematic diagrams of (a) n -ZnO/ p -ZnMgO/sapphire (1120), (b) p -ZnMgO/ n -ZnO/sapphire(1120) heterojunctions. The concentration of Sb in ZnMgO is 10%, and the concentrations of Ga in ZnO are changed from 0.1 to 5.0%.

et al. fabricated p -ZnMgO/ n -ZnO heterostructures by a PLD technique and observed good rectifying characteristics [8]. Thus, the I-V characteristics, field-effect transistor behaviors [9], optical gains [10], carrier composition dependences of the internal electric fields [11] have been reported for ZnMgO/ZnO heterostructures. However, there is no report concerning the electroluminescence (EL) from n -ZnO/ p -ZnMgO heterojunctions.

We have fabricated p - $\text{Zn}_{0.8}\text{Mg}_{0.2}\text{O}/n$ -ZnO heterostructures by a PLD technique and we investigated the relations between the I-V characteristics and the EL intensities. Clear EL was observed from the heterojunctions only when the ZnO layer was firstly deposited with 1.0% Ga, and then the p -type ZnMgO layer was deposited on it.

II. EXPERIMENTAL

Two types of heterojunctions, p -ZnMgO/ n -ZnO and n -ZnO/ p -ZnMgO were fabricated as shown schematically in Fig. 1; one has an n -ZnO film as the final layer of the structure, and the other a p -ZnMgO film as the final one. Sapphire (1120) substrates were degreased by organic solvent, and they were thermally cleaned at 800°C under 0.1

*This paper was presented at the 14th International Conference on Solid Films and Surfaces (ICSFS-14), Trinity College Dublin, Ireland, 29 June - 4 July, 2008.

†Corresponding author: aoyama@akita-pu.ac.jp

TABLE I: *n*-ZnO film properties doped with different Ga concentrations.

Ga Concentration [%]	Resistivity [ohm·cm]	Carrier Concentration [cm ⁻³]	Mobility [cm ² /Vs]
0.1	0.048	2.20×10^{18}	59.04
1.0	0.51	4.49×10^{17}	27.05
5.0	48.43	1.29×10^{16}	9.99

FIG. 2: The I-V characteristics of the *p*-ZnMgO/*n*-ZnO/sapphire(1120) heterostructure in Fig. 1(b). The Ga concentrations: (a) 0.1%, (b) 1.0%, and (c) 5.0%. The Sb concentration in ZnMgO is fixed at 10%.

Torr of oxygen atmosphere. After depositing a ZnO buffer layer, an *n*-ZnO layer was deposited by a PLD technique at 700°C under 0.01 Torr of oxygen atmosphere. Then, a metal mask was moved on the sample in the vacuum chamber, and a *p*-ZnMgO layer was deposited by changing the metal targets. The reverse heterostructure was fabricated by only changing the metal target sequence. The PLD conditions were as follows; 266 nm Nd:YAG laser with a repetition rate 10 Hz and a pulse energy density of 100 mJ, was used as the ablation source. The base pressure was 10^{-6} Torr and the distance between the sample and the target was 4 cm. Antimony-doped ZnMgO targets were fabricated using high-purity ZnO (99.999%) and MgO (99.99%), with Sb₂O₅ (99.99%) serving as the *p*-type doping agent. Gallium-doped ZnO targets were fabricated in the same way with Ga₂O₃ (99.99%) serving as the *n*-type doping agent. The Sb concentration was fixed at 10% and the Ga concentration was changed from 0.1 to 5.0%. Finally, the Al electrodes were deposited by using conventional evaporation equipments. The carrier concentration, the resistivity and the carrier mobility were measured by the Hall effect. The conduction type of high resistivity samples was decided by a heated probe measurement method. The EL spectra were obtained by using a FICS type spectrometer (Oriel, Ltd.) and a Newton type CCD detector (Andor, Ltd). The single acquisition time of the signal was 5 s and the signal integration was done by the repetition of 10 times.

III. RESULTS AND DISCUSSION

Table I shows the resistivity, the carrier concentrations and the carrier mobility for the *n*-type ZnO films. Contrary to our conventional expectation, the resistivity is in-

creased and the carrier concentrations are decreased from 10^{18} to 10^{16} cm⁻³, as the Ga concentrations increase from 0.1 to 5.0%. The largest electron mobility, 59 cm²/Vs is obtained for the ZnO film doped with 0.1% of Ga. This suggests that the film quality seems the best for 0.1% Ga doping.

The I-V characteristics of the *p*-ZnMgO/*n*-ZnO heterojunctions are shown in Fig. 2. Preliminary study using the heated probe method shows that the highest carrier concentration in *p*-type ZnMgO film is obtained by 10% Sb doping. The junction using the *n*-ZnO layer with 0.1% Ga doping indicates only an Ohmic contact with the *p*-type ZnMgO layer. The junction using the 5% Ga doping layer shows the best rectifying behavior. Rough estimation of the diode ideality factor indicates about 140 for this junction. The junction using the 1.0% Ga doping layer shows only a weak rectifying behavior with the ideality factor of about 390 and the forward current of 1.5 mA. All the heterojunctions of the reverse *n*-ZnO/*p*-ZnMgO structure show only Ohmic contacts.

No EL was observed for the heterostructures shown in Fig. 1(a). No EL was observed for the Ga concentrations of 0.1% and 5.0% in the heterostructure shown in Fig. 1(b). As shown in Fig. 3, clear EL spectra were observed only from the *p*-ZnMgO/*n*-ZnO heterojunction with 1.0% Ga doping layer in Fig. 1(b). The EL started from the 10V of the forward bias and it increased up to 20V. The spectra stretch from about 400 to 650 nm wave length. No EL was observed under reverse bias conditions for this heterojunction.

The results in Table I suggest that the 0.1% Ga concentration is enough for sufficient doping elements for *n*-type conduction and that the increase in Ga deteriorates the crystallinity of the ZnO films. The Ohmic behavior for this ZnMgO/ZnO junction in Fig. 1(b) implies that the

FIG. 3: The electroluminescence (EL) spectra of the p -ZnMgO/ n -ZnO heterostructure in Fig. 1(b). The Sb concentration in ZnMgO is 10% and the Ga concentration in ZnO is 1.0%. The forward bias was changed up to 30 V and no EL was observed under reverse bias conditions.

junction type is rather an n - i (intrinsic) junction. As the Ga concentration increases from 0.1 to 1.0% in the ZnO layer, a weak rectifying behavior appears. This result can be interpreted from a co-doping model; one is the original Sb atoms in ZnMgO layer and the other Ga atoms diffused from the ZnO layer. As the Ga concentration increases in the ZnO layer, the Ga concentration is also increased in the ZnMgO layer. Large number of Sb atoms is implied to sit originally in the Zn site in the ZnMgO layer, and they can replace with the diffused Ga atoms. Especially in the vicinity of the junction, the increased Sb atoms in O site work as a p -type dopant. As the Ga concentration

increases further from 1.0 to 5.0% in the ZnO layer, the diode ideality factor is improved from about 390 to 140 but the resistivity increase in the ZnO region seems to decrease the forward currents leading to no EL from the junction.

IV. SUMMARY

The p -Zn_{0.8}Mg_{0.2}O/ n -ZnO heterojunctions have been fabricated by a pulsed laser deposition (PLD) technique and the relations between the I-V and the electroluminescence (EL) characteristics were investigated. Ga is used as an n -type dopant and its concentration was changed from 0.1 to 5.0%. Sb is used as a p -type dopant at a fixed concentration of 10% because the ZnMgO film shows the best p -type characteristic for this concentration. The different Ga concentrations in n -type ZnO layers show different I-V and EL characteristics for the ZnMgO/ZnO heterojunctions. The 0.1% of Ga in the ZnO film shows the lowest resistivity (0.048 ohm-cm) and the highest electron mobility (59 cm²/Vs), however, the ZnMgO/ZnO junction shows only an Ohmic contact and no EL was observed. The heterostructure composed of the ZnO layer with 5.0% Ga shows the best rectifying behavior, however, no EL was observed. The 1.0% of Ga in the film shows the middle resistivity (0.51 ohm-cm) and the middle electron mobility (27 cm²/Vs). The ZnMgO/ZnO heterojunction shows only a weak rectifying behavior but clear EL is observed. The threshold voltage of the EL is about 10 V and the EL intensity is increased with the forward biases up to 20 V. No emission was observed under reverse bias conditions. No emission was observed from other reverse heterojunction structure. These results indicate that the EL from ZnMgO/ZnO junctions does not necessarily require good ideality factors of the diodes.

- [1] Y. I. Alivov, J. E. Nostrand, D. C. Look, M. V. Chukichev, and B. M. Ataev, Appl. Phys. Lett. **83**, 2943 (2003).
- [2] Y. I. Alivov, E. V. Kalinina, A. E. Cherenkov, D. C. Look, B. M. Ataev, A. K. Omaev, M. V. Chukichev, and D. M. Bagnall, Appl. Phys. Lett. **83**, 4719 (2003).
- [3] D.-K. Hwang, S.-H. Kang, J.-H. Lim, E.-J. Yang, J.-Y. Oh, J.-H. Yang, and S.-J. Park, Appl. Phys. Lett. **86**, 222101 (2005).
- [4] Ya. I. Alivov, Ü. Özgür, S. Dogan, D. Johnstone, V. Avrutin, N. Onojima, C. Liu, J. Xie, Q. Fan, and H. Morkoc, Appl. Phys. Lett. **86**, 241108 (2005).
- [5] J. D. Ye, S. L. Gu, S. M. Zhu, W. Liu, S. M. Liu, R. Zhang, Y. Shi, and Y. D. Zheng, Appl. Phys. Lett. **88**, 182112 (2006).
- [6] Y. R. Ryu, J. A. Lubguban, T. S. Lee, H. W. White, T. S. Jeong, and C. J. Youn, Appl. Phys. Lett. **90**, 131115 (2007).
- [7] C. Yuen, S. F. Yu, S. P. Lau, Rusli, and T. P. Chen, Appl. Phys. Lett. **86**, 241111 (2005).
- [8] H. Yang, Y. Li, D. P. Norton, S. J. Pearton, S. Jung, F. Ren, and L. A. Boatner, Appl. Phys. Lett. **86**, 172103 (2005).
- [9] T. V. Shubina, *et al.*, Appl. Phys. Lett. **91**, 201104 (2007).
- [10] S. Sesa, M. Ozaki, K. Koike, M. Yano, and M. Inoue, Appl. Phys. Lett. **89**, 053502 (2006).
- [11] T. Bretagnon, P. Lefebvre, T. Guillet, T. Tailercio, B. Gil, and C. Morhain, Appl. Phys. Lett. **90**, 201912 (2007).