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A route to improved extraction efficiency of light-emitting diodes

H. Zhu,[1,2] C. X. Shan,[1,a)] L. K. Wang,[1,2] Y. Yang,[1,2] J. Y. Zhang,[1] B. Yao,[1] D. Z. Shen,[1] and X. W. Fan[1]
[1]*Key Laboratory of Excited State Processes, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin 130033, People's Republic of China*
[2]*Graduate School of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*

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The electroluminescence from an *n*-MgZnO/*i*-ZnO/MgO/*p*-GaN asymmetric double heterojunction has been demonstrated. With the injection of electrons from *n*-MgZnO and holes from *p*-GaN, an intense ultraviolet emission coming from the ZnO active layer was observed. It is revealed that the emission intensity of the diode recorded from the MgZnO side is significantly larger than that from the MgO side because of the asymmetric waveguide structure formed by the lower refractive index of MgO than that of MgZnO. The asymmetric waveguide structure reported in this letter may promise a simple and effective route to light-emitting diodes with improved light-extraction efficiency. © *2010 American Institute of Physics*. [doi:10.1063/1.3301614]

Short wavelength light-emitting diodes (LEDs) have witnessed a number of milestone progresses in recent years,[1–3] and improving the light-extraction efficiency has been one of the most important issues in the further development of ultraviolet-blue LEDs.[4] A variety of methods have been employed to improve the extraction efficiency of LEDs. A widely employed route is a texturing on transparent electrodes.[5–7] However, surface texturing requires expensive and energy-consuming process, and the long exposure to etchants in the texturing process will degrade the performance of LEDs. Photonic crystal and conductive omnidirectional metal reflector (ODR) have also been used to increase the extraction efficiency.[8–11] However, the extrinsic photonic crystal or ODR will inevitably increase the cost, size, and complexity of LEDs. If an intrinsic modification on the structure of LEDs can be proved to be useful for enhancing the extraction efficiency of LEDs, the importance and significance of this route will be self-evident.

In this letter, an *n*-MgZnO/*i*-ZnO/MgO/*p*-GaN asymmetric double heterojunction (ADH) diode has been designed and prepared. Because of the much smaller refraction index of MgO than that of MgZnO, the emitted light will tend to emit from the MgZnO side (top surface) instead of the MgO side (bottom surface). Consequently, the light extraction of the diode from the top surface is enhanced significantly.

The ADH LED is prepared by depositing MgO, *i*-ZnO, and *n*-MgZnO in sequence onto a commercial available *p*-GaN/sapphire template using a metal-organic chemical vapor deposition technique. The GaN layer shows a *p*-type conduction with a hole concentration and mobility of about 3.0×10^{17} cm^{-3} and 10 cm^2 V^{-1} s^{-1}, respectively. The precursors used for the MgO, ZnO, and MgZnO growths were biscyclopentadienyl-Mg, diethylzinc and high purity (99.999%) oxygen, and nitrogen was used as a carrier gas. The as-grown MgZnO film showed *n*-type conduction with an electron concentration of 2.5×10^{17} cm^{-3} and a mobility of 2.0 cm^2 V^{-1} s^{-1}. The Mg content in the $Mg_xZn_{1-x}O$ film determined by x-ray photoelectron spectroscopy is 18%. Photoluminescence (PL) spectra of the films were recorded in a JY-630 micro-Raman spectrometer with the 325 nm line of a He–Cd laser as the excitation source. Electroluminescence (EL) measurements were carried out in a Hitachi F4500 spectrometer. The EL intensity distribution of the device was computed using crosslight PICS3D simulation software.

The inset of Fig. 1 shows a schematic illustration of the ADH diode. It consists of a 2 μm *p*-type GaN layer, a 30 nm MgO dielectric layer, a 3 nm ZnO active layer, and a 350 nm *n*-type $Mg_{0.18}Zn_{0.82}O$ layer. The current-voltage (*I-V*) curve of the ADH LED structure is shown in Fig. 1. The turn-on voltage derived from the *I-V* curve is about 10 V. The relatively large turn-on voltage may be due to the relatively high resistance of the MgO layer.

Shown in Fig. 2 are the room temperature EL spectra of the ADH LED collected from the top and bottom surface under the same injection current, which will be named as top surface spectrum and bottom surface spectrum, respectively, in the following text for simplicity. Note that the bottom surface spectrum has been magnified by three times for comparison. One can see that both spectra show a broad emission at around 400 nm, which may come from the transition of the defect levels in the ZnO or $Mg_{0.18}Zn_{0.82}O$ layer. Besides the broad emission, the top surface spectrum shows a distinct ultraviolet (UV) emission peak at 363 nm.

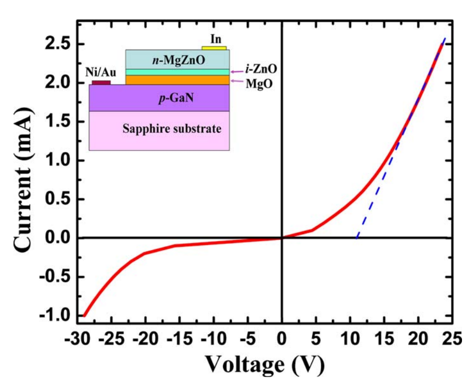

FIG. 1. (Color online) Typical *I-V* curve of the diode, revealing good rectifying behavior with a turn-on voltage of about 10 V. Note that the dashed line is a guide to the eyes. The inset illustrates the structure of the *n*-$Mg_{0.18}Zn_{0.82}O$/*i*-ZnO/MgO/*p*-GaN ADH LED.

a)Electronic mail: phycxshan@yahoo.com.cn.

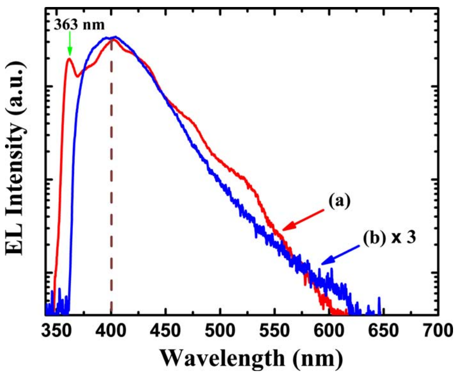

FIG. 2. (Color online) Room-temperature EL spectra of the n-$Mg_{0.18}Zn_{0.82}O$/i-ZnO/MgO/p-GaN ADH diode collected from the top and bottom surface under the same injection current, note that the spectrum from the bottom surface has been magnified by three times.

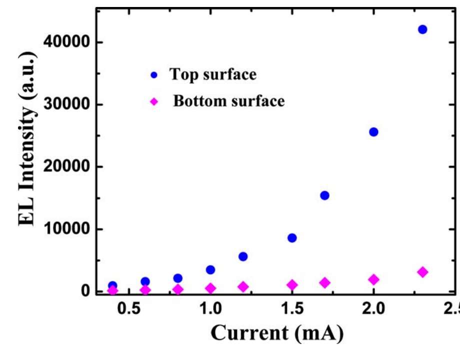

FIG. 4. (Color online) The integrated EL intensity recorded from the top and bottom surface of the diode by bonding a GaN/sapphire template on the MgZnO surface at room temperature, revealing significant enhancement in the light extraction from the top surface.

In order to explore the origin of the UV emission at 363 nm, the PL spectra of the p-GaN layer and n-$Mg_{0.18}ZnO_{0.82}$/i-ZnO/MgO structure have been measured, as illustrated in Fig. 3. The spectrum of the p-GaN is dominated by a broad peak centered at about 435 nm, which is frequently observed in Mg doped p-GaN, and can be attributed to transition between conduction band electrons or donors and Mg-related acceptors.[12] The spectrum of the n-$Mg_{0.18}ZnO_{0.82}$/i-ZnO/MgO structure shows two intense emission bands at 340 nm (3.65 eV) and 367 nm (3.37 eV). The former can be attributed to the near-band-edge emission of the $Mg_{0.18}Zn_{0.82}O$ film because its position is very close to the band gap of $Mg_{0.18}Zn_{0.82}O$ (3.68 eV),[13] while the latter is from the ZnO active layer, and the blueshift comparing with the band gap of ZnO is due to the quantum confinement effect caused by the two-dimensional potential well formed in the heterojunction considering the thickness of ZnO is only 3 nm.[14] The well accordance of the PL and EL emission confirms that the EL emission at 363 nm comes from the exciton recombination in the ZnO active layer. Note that 363 nm is the shortest EL emission ever reported in ZnO-based pn junctions.[15] This peak is absent in the spectrum recorded from the bottom surface, which is a result of the absorption by the GaN layer.

A schematic diagram of the band alignments of the ADH diode under forward bias revealing the mechanism of the EL emission is shown in the inset of Fig. 3. The carrier transportation process in similar p-GaN/MgO/n-Zn(Mg)O heterojunctions has been detailed in our previous publication.[16,17] Briefly, electrons in the n-MgZnO layer will drift into the ZnO layer under forward bias, and the large conduction band offset (3.55 eV) at the ZnO/MgO interface will prevent electrons from passing across the MgO layer and entering into the GaN layer. As for holes, the barrier height that hinders the holes in p-GaN from entering into the ZnO is much smaller (0.9 eV), and the effective thickness of the barrier will decrease significantly due to the band bending of the MgO layer under the forward bias. Consequently, holes in the p-GaN layer can enter into the ZnO. As a result, efficient emission from the ZnO active layer was obtained.

Another noteworthy phenomenon in the EL of the ADH LED is that the integrated emission intensity collected from the top surface is much larger than that from the bottom surface. To verify this discrepancy, a GaN/sapphire template was placed onto the top surface of the diode, and the emission from the top and bottom surface of the diode is collected. In this way, the possible interference caused by the GaN or sapphire can be avoided, the results of which are shown in Fig. 4. As evidenced from the figure, the integrated intensity recorded from the top surface is significantly larger than that from the bottom surface. In order to illustrate the discrepancy, the EL intensity distribution of the device was computed using PICS3D simulation software. Figure 5(a) shows the simulation of the two-dimensional optical field profile in the device. A calculation of optical field intensity distribution in the ADH structure with the indicated refractive index and thickness of each layer is shown in Fig. 5(b). As can be seen, the optical intensity recorded from the bottom surface is much weaker than that from the top surface.

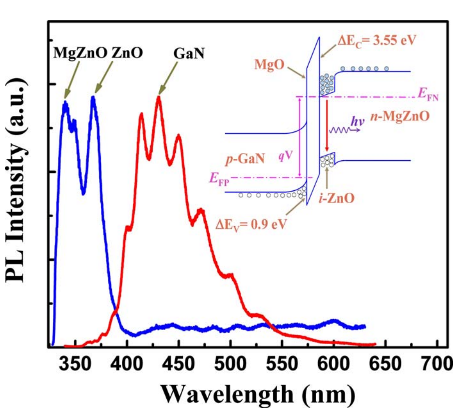

FIG. 3. (Color online) Normalized PL spectra of the n-$Mg_{0.18}Zn_{0.82}O$/i-ZnO/MgO structure and p-GaN layer. The inset shows the diagram of the band alignment of the n-$Mg_{0.18}Zn_{0.82}O$/i-ZnO/MgO/p-GaN ADH diode under forward bias.

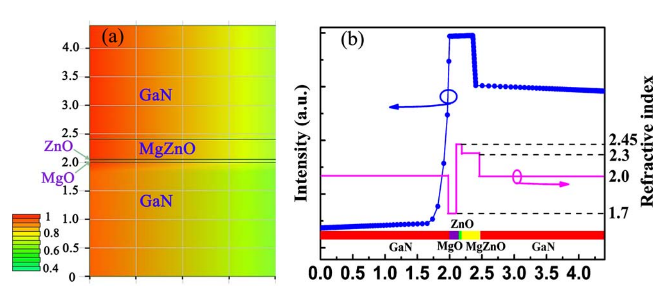

FIG. 5. (Color online) (a) The simulation of the two-dimensional optical field pattern in the device. (b) The computed optical field distribution in the ADH structure with the indicated refractive index and thickness of each layer.

This discrepancy is proposed to result from the asymmetric waveguide structure formed in the ADH diode because the refractive index of ZnO (2.45) and $Mg_{0.18}Zn_{0.82}O$ (2.3) is larger than those of MgO (1.7). The lower refractive index of MgO will decrease the penetration of the guided optical mode into the MgO layer. In other words most of the optical field will be distributed in the ZnO and MgZnO layer, thus the light extraction from the top surface will be enhanced. In fact, MgO has been employed as a waveguide for its smaller refractive index than ZnO, and random laser with low scattering loss has been realized in ZnO film.[18] Similar phenomena have also been observed in GaInN and AlGaInP LEDs, in which a silver layer with low-refractive-index was employed to increase the light extraction efficiency.[4]

In conclusion, an n-$Mg_{0.18}Zn_{0.82}O$/i-ZnO/MgO/p-GaN ADH LED has been designed and fabricated. An intense UV EL emission peak at 363 nm has been observed from the diode, which is the shortest EL emission ever reported in ZnO-based *pn* junctions. The asymmetric waveguide formed in this ADH structure because of the discrepancy in the refractive index of MgO and $Mg_{0.18}Zn_{0.82}O$ increases the light extraction efficiency of the diode. We note that this asymmetric waveguide structure may be applicable in other LEDs, and thus open a simple route to LEDs with improved extraction efficiency.

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