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Effect of the thickness of undoped GaN interlayers between multiple quantum wells and the p-doped layer on the performance of GaN light-emitting diodes

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Abstract: InGaN based light-emitting diodes (LEDs) with undoped GaN interlayer of variant thicknesses grown by metal-organic chemical vapor deposition technique have been investigated. It was found that the thickness of undoped GaN interlayers affected LEDs' performance greatly. The LED with 50 nm undoped GaN interlayer showed higher light output power and lower reverse-leakage current compared with the others at 20 mA. Based on electrical and optical characteristics analysis and numerical simulation, these improvements are mainly attributed to the improvement of the quality of depletion region by inserting an undoped GaN layer, as well as reduction of the Shockley–Read–Hall recombination in InGaN/GaN MQWs.

OCIS codes: (230.3670) Light-emitting diodes; (230.0250) Optoelectronics.

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1. Introduction

InGaN/GaN based high-brightness light-emitting diodes (LEDs) have attracted much attention because of their applications in signage, back lighting and general illumination. The emission efficiency of InGaN/GaN LEDs is closely connected with recombination mechanisms in multiple quantum wells (MQWs). Further study on recombination mechanisms is highly desirable which is beneficial to improve LED performance, though the emission efficiencies have been improved drastically during the last few years. There have been many reports about the recombination dynamics in multiple quantum wells (MQWs) such as non-uniform carrier distribution in MQWs [1], limited injection efficiency [2], carrier leakage out of the active region [3], compositional fluctuations and carrier localization [4], Auger recombination [5], polarization fields [6] and the quantum confined Stark effect (QCSE) [7]. In this paper, we studied InGaN based LEDs with undoped GaN interlayers of different thicknesses. It was found that the thickness of undoped GaN interlayers affected the LED's performance greatly. The influence mechanism of the undoped GaN interlayer thickness was investigated, as well as reduction of the Shockley–Read–Hall recombination in InGaN/GaN MQWs.

2. Experimental Details

The LED wafers were grown on c-sapphire substrate using metal-organic chemical vapor deposition (MOCVD) with the Thomas Swan closely spaced showerhead reactor. The epitaxial wafer structures consisted of a 25 nm thick low-temperature GaN nucleation layer, a 2.0 µm thick undoped GaN layer, a 2.0 µm thick Si-doped n-GaN layer (*n*-doping =5×10^{18} cm^{-3}). The active region consisted of six 2.8-nm-thick $In_{0.16}Ga_{0.84}N$ QWs, separated by five10-nm-thick GaN barriers. On top of the last QW was an undoped GaN interlayer, and a 20 nm thick p-type $Al_{0.1}Ga_{0.9}N$ and 170 nm thick Mg doped p-GaN were deposited at last. Five LED samples were grown under the same growth condition, corresponded with 5 nm, 15 nm, 30 nm, 50 nm, 70 nm undoped GaN interlayers. LED chips with a size of 300×300 μm^2 were fabricated using a conventional mesa structure method. Wafers were processed into lateral LED structures and left unencapsulated in wafer form. Current–Voltage (*I*–*V*) characteristics of the fabricated chips were measured at room temperature. The light output powers of the LED chips were measured by an integrating sphere with a calibrated power meter.

3. Results and Discussion

The experimental and simulated current-voltage (*I*-*V*) characteristics of InGaN/GaN LEDs with different undoped GaN interlayer thickness are plotted in Fig. 1, which shows the same tendency of forward voltage between the experimental data and our simulations. As undoped GaN interlayer thickness increased from 5 nm to 70 nm, under an injection current of 20 mA, the experimental and simulated forward voltages of chips were ascending from 3.17 V to 3.28 V and 3.13 V to 3.22 V, respectively. It is considered that the slight increase in forward voltage is mainly attributed to the increase of undoped GaN interlayer thickness which deteriorated the electrical conductivity of LED chips.

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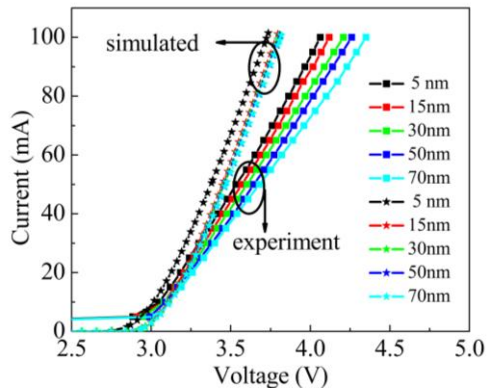

Fig. 1. Experimental (square) and simulated (star) current-voltage (*I-V*) characteristics of all samples.

Figure 2 presents the dependence of the luminance intensity on the injection current *(L-I)* characteristics of all samples. It can be clearly seen that the luminance intensity of the LEDs increased sharply with the thickness of undoped GaN interlayer augmented from 5 nm to 50 nm, and then decreased as the thickness further increased. Furthermore, the luminance intensity of the LED with 50 nm undoped GaN layer (65 mcd) exhibited improvement of about 260% in light output power compared with that with 5 nm undoped GaN layer (18 mcd) at 20 mA. Though the increased undoped GaN interlayer can let more light escape from MQWs, and thus enhance the light extraction efficiency. However, it is considered that this mechanism cannot fully explain such a large increase in light output power, and further explanation will be given later.

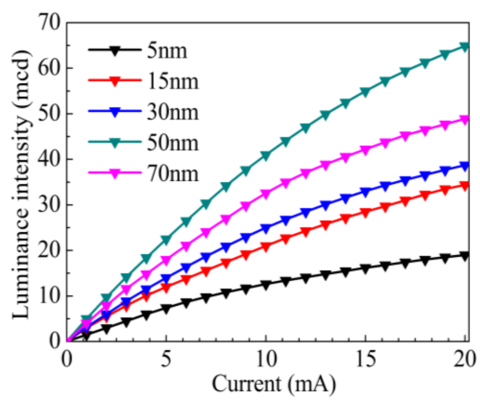

Fig. 2. The dependence of luminance intensities on current of all samples.

The experimental peak wavelength and full width at half maximum (FWHM) of the InGaN/GaN LED chips as a function of thicknesses of undoped GaN interlayers was shown in Fig. 3(a). The FWHMs of all samples almost kept as a constant of around 19 nm, indicating that the quality of LEDs did not get worse as the undoped GaN interlayer thickness increased. Because the undoped GaN interlayer thickness increased from 5 nm to 50 nm lead to an augment of the quantum-confined Stark effect [8], a red shift of the peak wavelength was observed. The light output power and reverse leakage current of the samples are also indicated in Fig. 3(b). The light output power ascended in parabolic pattern as the thickness of undoped GaN increased from 5 nm to 50 nm, and the explanation will be given later. Note that when the thickness of undoped GaN interlayer is 50nm, the light output power shows the largest value. On the other hand, as the thickness of undoped GaN interlayer increased from 5 nm to 50 nm,

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under −8.0 V reverse bias, the reverse leakage current decreased from 0.69 µA to 0.01 µA, and then remained almost at 0.01 µA.

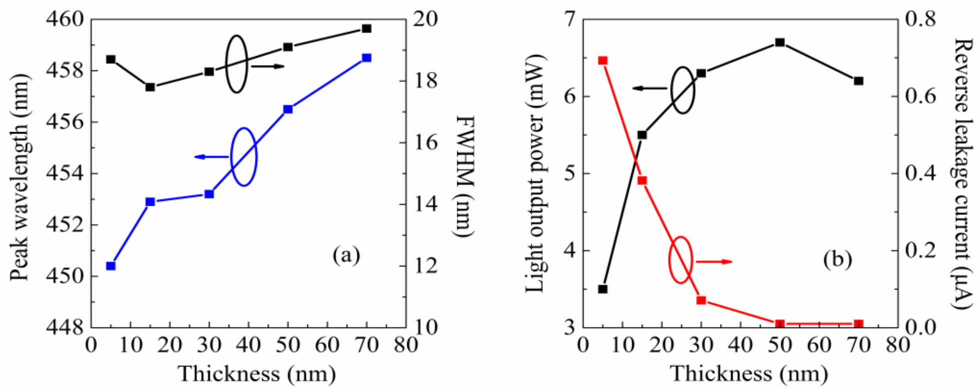

Fig. 3. (a) Experimental peak wavelength and FWHM and (b) measured light output power at 20mAand reverse leakage current at −8V as a function of undoped GaN interlayer thickness.

Kuksenkov *et al* [9] and Cao *et al* [10] found that the reverse leakage current was closely connected with the defect states in the depletion region. Because of the low growth temperature, there may be more defects in InGaN QWs compared to the undoped GaN interlayer, and the improved depletion region quality by increased undoped GaN thickness leads to a reduction in the reverse leakage current.

In our results, the thickness of undoped interlayer GaN affected light output power greatly, indicating that the undoped interlayer GaN may decrease the nonradiative recombination. Nonradiative recombination consists of Shockley–Read–Hall (SRH) recombination process and Auger recombination process. We have simulated that the Auger recombination is much smaller than SRH recombination which is consistent with Kuo's results that the Auger recombination can be neglected under the case that the carrier density is below 1×10^{20} cm^{-3} [11], the value of Auger coefficient should be in the order of 1×10^{-34} cm^6 /s, which is a relatively small figure. Thus, the improved performances of LEDs with 50 nm undoped GaN interlayer are probably mainly attributed to the reduction of the SRH recombination in InGaN/GaN MQWs. Shockely [12] first described that the semiconductor diodes would deviate from the ideal behavior when generation-recombination (GR) processes took place in the depletion region. Sah *et al* [13] and Choo [14] confirmed that SRH GR in the depletion region could dominate the characteristics of semiconductor diodes. Nash *et al* [15] used lithography and etching spatially to remove parts of the depletion region which helped to reduce the total SRH recombination and got improved light emission and less reverse leakage in AlInSb based midinfrared LEDs. In order to support the experimental results, the performance of these LEDs was investigated numerically with the APSYS simulation program, which was developed by the Crosslight Software Inc [16]. The operating temperature is assumed to be 300K.

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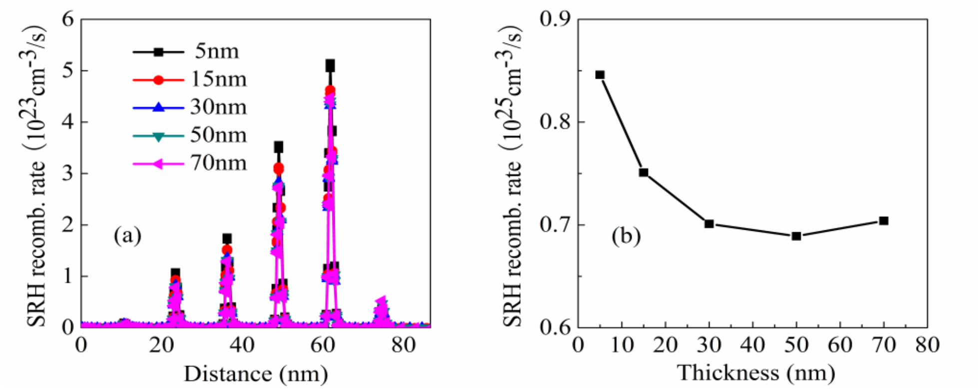

Fig. 4. (a) Simulated distribution of SRH recombination rate and (b) calculated total SRH recombination rate in MQWs of all samples at 20mA.

Figure 4(a) shows the SRH recombination rate distribution in the active region of LEDs with different undoped GaN thicknesses, under an injection current of 20 mA. As the undoped GaN interlayer thickness increased, SRH recombination rate decreased in every quantum well. Total SRH recombination rate in MQWs with different undoped GaN interlayer thickness was indicated in Fig. 4(b). Please note that the variation trend of SRH recombination rate is similar with that of light output power in those samples shown in the above. The SRH recombination rate of the LED chips with 50 nm undoped GaN interlayer is the minimum among all samples. The electrical and optical characteristics of LED were greatly improved by inserting an undoped GaN layer of appropriate thickness which is beneficial to improve the depletion region quality, and thus decrease the nonradiative recombination in MQWs. As the undoped GaN thickness further ascended to 70 nm, the total SRH recombination rate was slightly raised which is consistent with the drop in light output power.

4. Conclusions

We have investigated the characteristics of InGaN/GaN LEDs with undoped GaN interlayer of different thickness sandwiched between InGaN/GaN MQWs and the p-type layer. Both the simulative and experimental results indicated that undoped GaN interlayer thickness affected LEDs' performance greatly. LEDs with 50 nm undoped GaN interlayer showed maximal light output power and relatively small reverse current leakage. The improved electrical and optical characteristics of these structures suggested that nonradiative SRH recombination in InGaN/GaN MQWs was reduced by inserting an undoped GaN layer with appropriate thickness.

Acknowledgments

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