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Enhanced Luminescence Efficiency of InGaN/GaN Multiple Quantum Wells by A Strain Relief Layer and Proper Si Doping

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1. Introduction

In recent years, III-V nitride light-emitting diodes (LEDs) have been intensively developed and employed for versatile applications in the area of indicators and illuminators, due to their extensive spectra covering from ultraviolet to near-infrared [1]. However, the performances of GaN-based LEDs are very sensitive to the growth of high quality epilayers. These LEDs usually utilize InGaN/GaN multiple quantum wells (MQWs) as the active layer. However, InGaN ternary alloys suffer many problems, such as low miscibility of InN in GaN, high volatility of InN after subsequently high temperature of the p-GaN growth, and large lattice mismatch between InGaN and GaN. Especially, a large piezoelectric field-induced quantum-confined Stark effect (QCSE) in the MQWs region will result in a spatial separation of electrons and holes due to large lattice mismatch [2]. As a result, the poor internal quantum efficiency of InGaN active layer is obtained.

On the other hand, a proper Si doping is introduced into the selected barrier of MQWs in order to enhance the luminescence efficiency. It has been reported that Si doping into the MQWs obviously affects the characteristics of InGaN-based LEDs [3]. It is shown that the high crystal and interfacial qualities of the InGaN/GaN LEDs can be achieved as a result of Si doping in the barrier of MQWs. Furthermore, the localization effect is induced by slightly doping Si in the barrier of MQWs, it leads to an improvement in the carrier mobility [4]. These results indicated that the Si-doped barrier can be a hole blocking layer. The recombination center of electron and hole is sandwiched between the Si-doped barrier of MQWs and p-GaN layer.

In this study, a superlattice structure of $In_{0.08}Ga_{0.92}N$/GaN strain relief layer (SRL) was grown on the top of the n-GaN layer. A Si-doped layer was simultaneously introduced in the $In_{0.08}Ga_{0.92}N$/GaN SRL with different doping levels and positions. Their effects on the optical and electrical properties were discussed.

2. Experimental

The $In_{0.17}Ga_{0.83}N$/GaN MQW LED samples used in this study were grown by metal-organic chemical vapor deposition (MOCVD) on a c-face (0001) sapphire substrate. The LED structure consists of a 30 nm-thick GaN low-temperature nucleation layer, a 2 μm-thick undoped GaN epilayer, a 2 μm-thick Si-doped GaN epilayer, an InGaN/GaN MQW active layer, a 24 nm-thick Mg-doped $Al_{0.15}Ga_{0.85}N$ (40 Å)/GaN (20 Å) superlattices in order to increase the hole concentration, and finally a 260 nm-thick Mg-doped GaN cap layer. The MQW active layer consists of five periods of 3 nm-thick InGaN well layers and 10 nm-thick GaN barrier layers. For comparison, the same LED structure was also prepared, while the SRL was sandwiched between n-GaN and MQWs. The SRL consists of twelve periods of 1.5 nm-thick InGaN well and 7 nm-thick GaN barrier, which was grown at a constant temperature of 900°C.

In addition to study of SRL, Si-doped layer was also investigated to improve the luminescence efficiency. Table I lists the information on the flow rates and positions for Si doping in the SRL. The Si-doped layer has difference donor concentration from 0 to 3×10^{18} cm^{-3}. After the growth, the surface of the LEDs was partially etched until the n-GaN layer was exposed. The Ni-Au and Ti-Al-Ti-Au were deposited on p-GaN and exposed n-GaN surface as p-type and n-type electrode to complete the fabrication of LEDs, respectively.

Table I Si doping in the SRL with various flow rates and positions

LED	Si-doped SRL	
	first 9 barriers	last 3 barriers
A	0.04 sccm	0.04 sccm
B	0.004 sccm	0.2 sccm
C	0 sccm	0.2 sccm

3. Results and discussion

Figure 1 shows the time sequence of the structure and Si doping profiles during the growth of LEDs. It is also presented a growth procedure for MQWs active layer with a temperature ramping process. For each quantum well and barrier layer, the growth temperature was 860°C and 940°C, respectively, in order to improve the crystal quality of MQWs. It can be found that Si was doped in the medium of last three barriers of SRL for LED C. In addition, another batch of Si doping was simultaneously carried out in the first nine barriers of SRL, combine with Si doping in the last three barriers for LED A and B. However, the concentration of Si in the first nine barriers was lower than that of last three barriers for LED B.

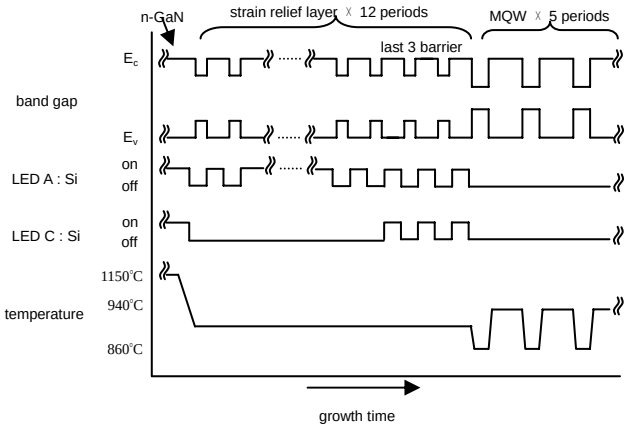

Fig. 1 Time sequence of the structure and Si doping profiles during the growth of strain relief layer.

Figure 2 shows the electroluminescence (EL) spectra of InGaN/GaN MQW LEDs with and without the SRL, the spectra were measured at different injection currents. A large blue-shift of the emission peak from LEDs without SRL was observed with the increase of the injection current, as shown in Fig. 2 (a). The largest blue-shift 10 nm, was obtained for LEDs without SRL from 471 to 461 nm, while that for the LEDs with SRL was only 2.5 nm with an injection current from 1 to 20 mA. Moreover, the EL intensity of the LEDs with SRL was higher than that of LEDs without SRL. In general, an InGaN/GaN MQW is adopted as the active layer. There is a large difference lattice mismatch between InN and GaN. As a result, the strain can produce a large piezoelectric field in the MQW active layer. And the piezoelectric field-induced QCSE can results in a spatial separation of electrons and holes, which leads to a significantly reduction of the internal quantum efficiency of the LEDs. Thus a larger blue-shift is a clear evidence that LEDs without the SRL suffer the stronger QCSE than those with the SRL do.

The typical power-voltage-current curves of Si-doped SRL LEDs at room temperature are depicted in Fig. 3. The output powers of LED B and C are higher than that of LED A. It indicates that the transmission of hole is effectively confined within the MQW by Si doping in the barrier of SRL. The energy band of last three barriers can be pulled down by increasing Si doping level, which may lead to the increase in hole barrier height. The output powers are about 15, 17.6, and 18.7 mW for LED A, B, and C, respectively. Furthermore, the properties of forward voltage are almost the same for these three LEDs.

4. Conclusion

We have demonstrated the properties of InGaN/GaN LEDs using a SRL between MQW and n-GaN for strain reducing. By inserting the SRL, the QCSE effect can be reduced. The blue-shift of EL peak is decreased from 10 to 2.5 nm with the injection current increasing from 1 to 20 mA. In addition, a Si-doped layer is also introduced in the InGaN/GaN SRL with a suitable doping level and position. Compare to LED A, the output power is increased more than 25% in LED C.

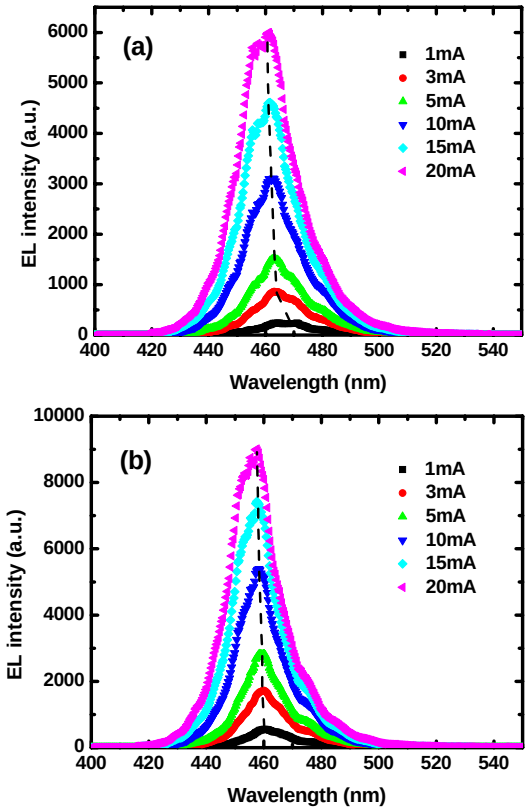

Fig. 2 The EL spectra as a function of the injection current for LEDs (a) without and (b) with a SRL.

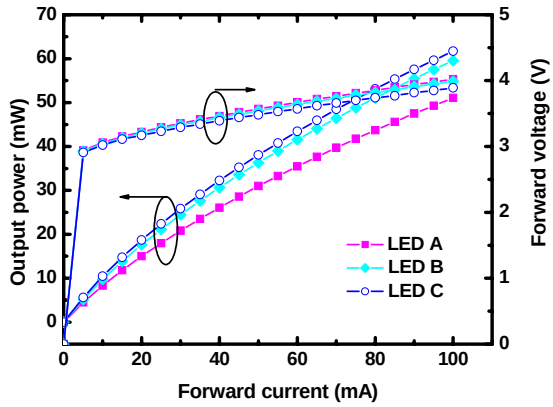

Fig. 3 Output power-voltage-current curves of Si-doped SRL LEDs at room temperature.

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