Influence of Prestrained Graded InGaN interlayer on the Optical Characteristics of InGaN/GaN MQW-based LEDs

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***Abstract - In this work, an InGaN/GaN multi-quantum well light emitting diode is designed with different kinds of prestrain layers (InGaN) inserted between the active region and n-GaN layer to demonstrate the effects of piezoelectric polarization on GaN-based LEDs. The device describes a GaN buffer layer which promotes charge injection by minimizing energy barrier between electrode and active layers. Compared to the conventional LED, more than 48.47% enhancement in the efficiency of the LED with prestrain layer can be observed which is attributed to the reduction of polarization field within MQW regions. The proposed device attains a high-efficiency of 81.94%, and minimized efficiency droop of 3.848% at an injection current of 10 mA with 16% In composition and has high-luminous power in the spectral range*.**

I. Introduction

Light-emitting diodes (LEDs) based on solid-state technology are increasingly used in a wide range of applications, owing to their high efficiency, poor power consumption, compact size, and enormous energy saving potentials[1].

Group III-nitride semiconductors with magnificent thermal & electrical stability and high quantum efficiency are the suitable characteristics for LED manufacturing [2][3]. However, it is still a great challenge to grow InGaN/GaN quantum well with high emission efficiency. GaN-based materials have strong polarization field along the *c*-plane direction, so the space charges induced by spontaneous and piezoelectric polarization fields accumulate at the interfaces of GaN heterostructure. Because of strong piezoelectric polarization (PZ) in InGaN/GaN multi-quantum well (MQW) induced by the large lattice mismatch between InGaN and GaN layers, Quantum-confined Stark effect (QCSE) inherits thus leading to the minimization of (EQE) external quantum efficiency. QCSE within the active region results in significant spatial separation of the electron and hole wave functions.

However, prestrained growth technique has attracted a lot of interest for its significant improvement on the efficiency of InGaN/GaN MQW. The deposition of prestrain layers prior to the growth of MQW creates a tensile strain in the barrier layer which is beneficial for the enhancement of the incorporation of larger-size indium (In) atoms in the wells. Moreover, the prestrained InGaN interlayer containing high In composition is beneficial for improvement of light emission efficiency due to the reduction of QCSE.

In this article, we have investigated the strain relaxation of the MQW with different In composition prestrained InGaN interlayer in LED structures. The basic parameters and their impact in device characteristics and output performance in InGaN/GaN MQW with GaN buffer layer are studied.

II. Device Structure and its Physics

To study the impact of various In composition prestrained InGaN interlayer, the commercially available Silvaco TCAD tool is used in this work.

All the samples used in this study are grown on silicon (Si) substrate as shown in Fig. 1(a). The conventional LED structure (LED_1) consists of 1 μm thick undoped GaN buffer layer grown at low temperature, 1.8 μm thick Si-doped n-GaN layer with a doping concentration of 1.5×10^{20} cm^{-3}, MQW active region comprising of four periods of quantum wells (InGaN with thickness of 4 nm and 15% In composition) and barriers (GaN with thickness of 9 nm), electron blocking layer (EBL) p-AlGaN of thickness 20 nm and doping concentration of 2.5×10^{18} cm^{-3}, 0.3 μm thick p-GaN layer. The respective band energy gaps of GaN and InGaN are considered to be 3.42 eV and 0.77 eV. The recombination rate coefficients of GaN and InGaN are 2×10^{-10} and 1.1×10^{-10} cm^3/s. GaN have lattice constant of 0.3189 nm [9]. The default values of Auger coefficient and carrier lifetime are 1×10^{-34} cm^6/s and 1×10^{-9} s respectively.

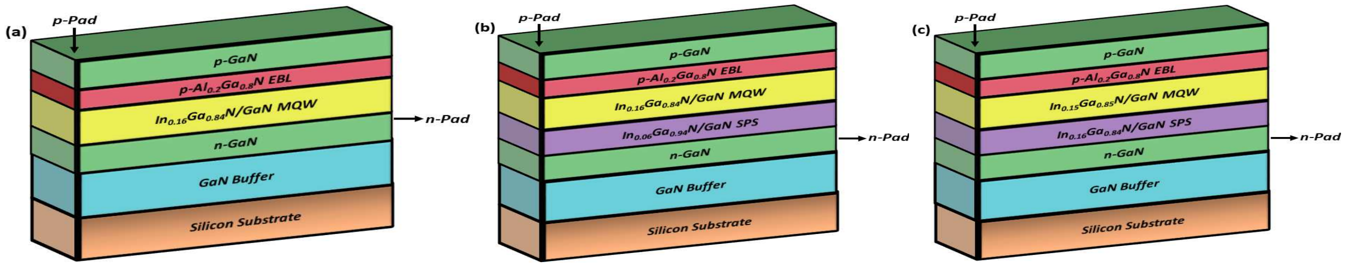

Fig. 1. Schematic Diagrams of LED_1, LED_2 and LED_3.

In an attempt to reduce the strain and PZ effect within the active region, we have proposed LEDs with prestrain interlayer structure. In Fig. 1(b)-(c), the LEDs with 8-pairs of InGaN (2 nm)/GaN (3 nm) superlattices (SPS) interlayer are grown in between the active region and n-GaN layers. The nominal In compositions of the prestrained InGaN interlayer are estimated to be 0.06 and 0.16 represented as LED_2 and LED_3 respectively.

III. Results and Discussion

In Fig. 2, EQE as a function of injection current is shown for the designed samples. LED_3 has the highest efficiency of 81.94% at an injection current of 10 mA. The inset shows a reduction in efficiency droop in LED_3 (3.848%) as compared to the other cases. The improvement of EQE for prestrain structures is mainly due to the partial strain relaxation within the active region, Due to this in each well the overlap of the electron and hole wave functions is improved and also there is less tilt of band-edge. It signifies that by inserting prestrain interlayer within the structure the polarization field could be reduced effectively.

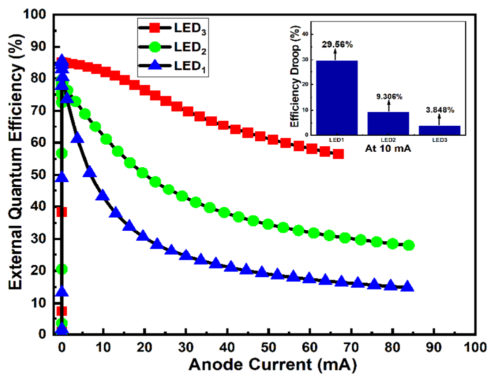

Fig. 2. Normalized efficiency for LED_1, LED_2 and LED_3.

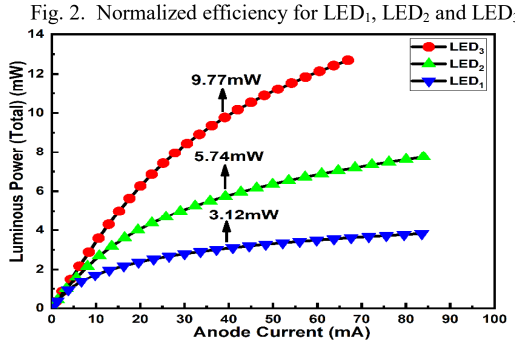

Fig. 3. Power-current curves for LED_1, LED_2 and LED_3.

Fig. 3 illustrates the measured light output power at 300K as a function of the injection current for these three designed LED structures which shows a superior optical power in LED_3 as compared to LED_1 and LED_2. At an injection current of 40 mA, the respective light output powers of LED_1, LED_2 and LED_3 are 3.12, 5.74 and 9.77 mW. The output powers with prestrain structures were 45.6 and 68.1% higher than the conventional one. This enhancement in the output power of LED_2 and LED_3 can be attributed to the release of the residual strain, decrease of PZ and QCSE, the enhancement of electron-hole recombination rate and the betterment of the crystal quality in MQWs.

IV Conclusion

The impact of indium composition in the prestrained InGaN interlayer on the strain relaxation of InGaN/GaN MQWs in LED structures was investigated. It was found that the strain of MQW layer in LED_3 with high In composition (~16%) prestrained interlayer was more relaxed and the degree of strain relaxation was higher than that of LED_2 with low In composition (~6%) prestrained layer. It also shows that LED_3 has poor QSCE and thus attains a large EQE of 81.94% and weaker efficiency droop of 3.848%. The prestrained InGaN interlayer containing high In composition is beneficial in releasing the strain of MQW and weakens QCSE so as to improve the optical properties of InGaN/GaN MQW LEDs.

Acknowledgment

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