Effects of a prestrained InGaN interlayer on the emission properties of InGaN/GaN multiple quantum wells in a laser diode structure*

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The electroluminescence (EL) and photoluminescence (PL) spectra of InGaN/GaN multiple quantum wells (MQWs) with a prestrained InGaN interlayer in a laser diode structure are investigated. When the injection current increases from 5 mA to 50 mA, the blueshift of the EL emission peak is 1 meV for the prestrained sample and 23 meV for a control sample with the conventional structure. Also, the internal quantum efficiency and the EL intensity at the injection current of 20 mA are increased by 71% and 65% respectively by inserting the prestrained InGaN interlayer. The reduced blueshift and the enhanced emission are attributed mainly to the reduced quantum-confined Stark effect (QCSE) in the prestrained sample. Such attributions are supported by the theoretical simulation results, which reveal the smaller piezoelectric field and the enhanced overlap of electron and hole wave functions in the prestrained sample. Therefore, the prestrained InGaN interlayer contributes to strain relaxation in the MQW layer and enhancement of light emission due to the reduction of QCSE.

Keywords: electroluminescence, quantum-confined Stark effect, InGaN/GaN quantum wells, laser diode

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1. Introduction

In recent years, GaN based semiconductors have brought significant changes in photonic device applications, and InGaN/GaN quantum wells (QWs) have been widely used as the active layers of light-emitting diodes (LEDs) and laser diodes (LDs) in the visible and ultraviolet ranges.[1–4] To further improve the performance of LEDs or LDs, it is important to understand the physical mechanisms of emission in such QWs. The piezoelectric field caused by the different lattice constants of InN and GaN leads to a potential tilt and strongly influences the emission characteristics of InGaN/GaN QWs,[5,6] a phenomenon called the quantum confined Stark effect (QCSE).[7,8] Because of this effect, the emission spectral peak is red-shifted and the carrier recombination rate is reduced. More efforts in the control of the QCSE in InGaN/GaN quantum wells are needed.

Recently, a prestrained growth technique has been developed wherein a low-indium prestrained InGaN layer is deposited before the growth of subsequent InGaN/GaN QWs.[9] As previously reported, with the prestrained InGaN middle layer, a tensile strain can be generated in the GaN barrier layer right above it such that the indium incorporation during the growth of the subsequent QWs becomes easier and the QCSE can be significantly reduced. There have been some experimental reports of fabricating orange-red and green LED structures by using the prestrained growth techniques,[9,10] but few investigations of blue LD structure growth techniques are undertaken. Especially few theoretical analyses have been reported about the effect of a prestrained InGaN interlayer on the emission properties of InGaN/GaN QWs. The influence of the prestrained interlayer on the control of QCSE in blue InGaN/GaN LD structures has not been fully discussed yet. In this paper, we report our investigation of the mechanism that improves the efficiency of blue LD structures with a prestrained InGaN interlayer, both theoretically and experimentally. The measurements show a more intense electroluminescence (EL) emission and a smaller emission peak blueshift of injection current-dependent EL in the prestrained sample. In addition, temperature dependent photoluminescence (PL) measurements show a higher internal quantum efficiency (IQE) in the prestrained sample. To investigate the strain relaxation of the InGaN/GaN QWs, the energy band and the overlap of electron and hole wave functions in the QWs are discussed and compared with those of a conventional structure. Also, the electric field in the QWs is investigated by numerical simulation to explain the results.

2. Sample structures and preparation conditions

The InGaN/GaN QWs LD samples were prepared for comparison to demonstrate the contribution of the prestrained growth technique. The control sample under study was grown on a *c*-plane sapphire substrate by metal-organic chemical vapor deposition. First, a 1-μm-thick undoped GaN layer was deposited on the substrate. Then, after the growth of a 3-μm Si-doped GaN layer, an n-type 3-nm $Al_{0.2}Ga_{0.8}N$/ 3-nm GaN super-lattice (SL) structure of 160 periods was deposited on

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the top. A 0.1-μm-thick unintentionally doped n-type GaN waveguide layer was grown on the top of the SL cladding layer. The QW structure was sandwiched between the n-type waveguide layer and a 60-nm-thick p-GaN layer. The QW structure included five periods of 2.5-nm-thick InGaN wells and 8-nm-thick GaN barriers. The average indium content of the QWs was 11% for blue emission. In the prestrained sample, an extra 10-nm-thick InGaN interlayer was inserted between the n-type waveguide layer and the MQWs. The nominal indium composition of the prestrained InGaN interlayer was estimated to be 0.03.

3. Experiments and discussion

The EL spectrum measurement was performed at room temperature when a continuous current was injected. Figures 1(a) and 1(b) show the EL spectra of the control sample and the prestrained sample at various injection current levels, with the variations in emission intensity and spectral features. In addition, multiple peaks in the EL spectra can be seen because of the Fabry–Pérot oscillation. Here, one can observe that the spectral peak of the prestrained sample (at 3.05 eV) is blueshifted from that of the control sample (at 2.89 eV) at injection current 20 mA. Due to the prestrain effect, a tensile strain is created in the GaN barrier layer, and the QCSE of QWs can be reduced, which results in the blueshifted emission peak. Because the potential fluctuation is effectively decreased[11] and the QCSE is reduced by inserting the prestrained layer, the linewidth of the prestrained sample is smaller than that of the control sample.

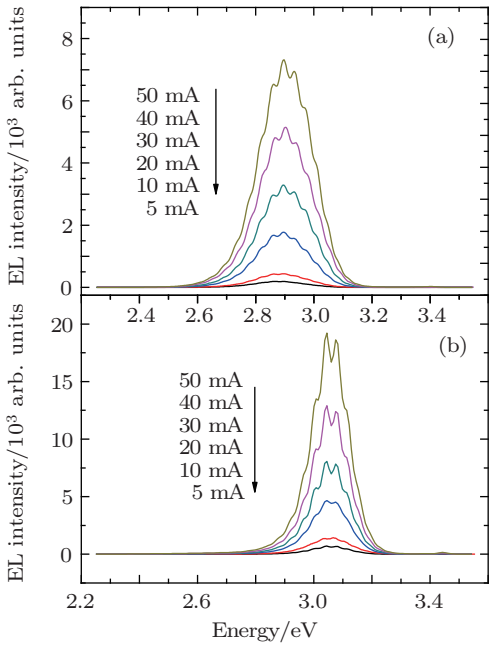


Fig. 1. (color online) EL spectra of (a) control sample and (b) prestrained sample at various injection current levels.

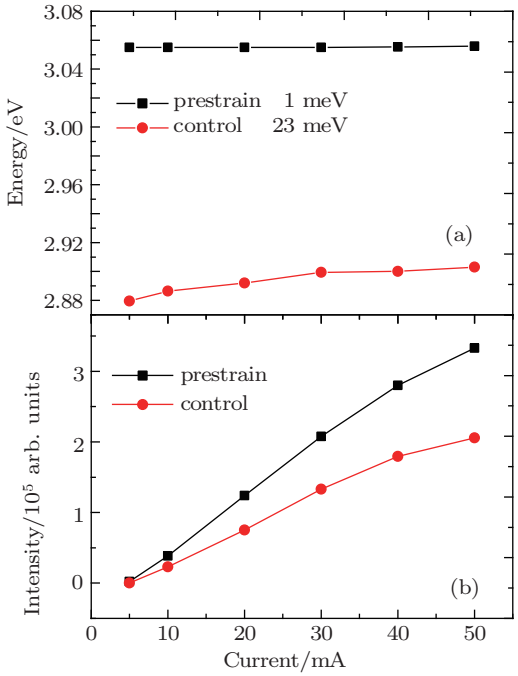


Fig. 2. (color online) (a) EL spectral peak shift and (b) integrated EL intensity as a function of injection current in control and prestrained samples.

The spectral peak variations with the injection current are shown in Fig. 2(a). When the injection current increases from 5 mA to 50 mA, the spectral peak of the control sample blueshifts by 23 meV (from 2.879 eV at 5 mA to 2.902 eV at 50 mA) as marked in the figure. In the same injection current range, the blueshift of the prestrained sample is only 1 meV (from 3.055 eV at 5 mA to 3.056 eV at 50 mA), which is much smaller than that of the control sample. The blueshift is attributed to the screening of QCSE.[12,13] Because of the strong piezoelectric field, the potential tilt in InGaN/GaN QWs leads to a redshift of the emission peak. When the density of carriers increases, these carriers can screen the DC fields in the QWs, thereby reducing the QCSE and hence leading to the blueshift behavior. As demonstrated in Fig. 2(a), the significantly smaller blueshift implies the relatively weaker QCSE in the prestrained sample. As shown in Fig. 2(b), the integrated EL intensity of the prestrained sample is larger than that of the control sample at various injection current levels. The EL intensity of the prestrained sample at the injection current of 20 mA is increased by 65%. Figure 3 shows the evolution of PL spectra for the two samples when they are pumped with excitation power density 50 W/cm^2 over a temperature range from 10 K to 300 K. As the temperature is decreased, nonradiative processes are reduced, and the radiative recombination becomes dominant, which leads to the increase of the PL intensity. The inset of Fig. 3 shows the temperature dependence of the normalized integrated PL intensity of the emission. Generally, the internal quantum efficiency (IQE) can be

defined as the ratio of the integrated PL intensity at 300 K to that measured at 10 K, which is based on the assumption of an internal efficiency of 100% at low temperatures. The IQE is about 24% for the prestrained sample, which is larger than that of the control sample (nearly 14%). There is a 71% increase in the IQE of the prestrained sample. To investigate the cause of the enhancement of emission intensity and the reduced QCSE, it is necessary to study the influence of the prestrained interlayer on the QCSE in QWs.

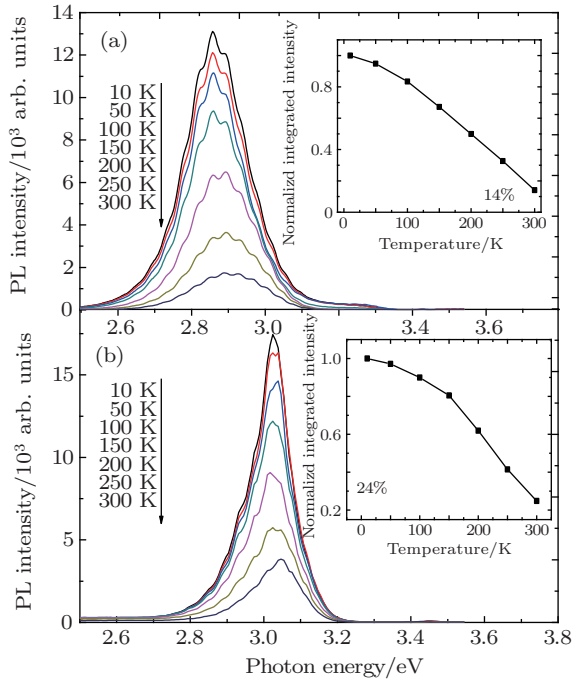


Fig. 3. (color online) PL spectra in the temperature range from 10 K to 300 K for (a) control sample and (b) prestrained sample. Inset shows the temperature dependence of the integrated PL intensity of emission.

To further investigate the QCSE difference between the prestrained sample and the control sample, simulations of these structures were performed using the modeling software APSYS from Crosslight Software Inc. The APSYS simulator is based on the drift-diffusion theory for carrier transports coupled with the self-consistent solution of Poisson and Schrödinger equations in the active region.[14,15] On the other hand, the spontaneous and piezoelectric polarization models for the built-in electric field are taken into account according to the model of Fiorentini *et al.*[16] In the simulations, the indium composition of the InGaN prestrained layer is assumed to be 3%. In addition, the p-doping concentration is set to 1.2×10^{18} cm^{-3} and the n-doping concentration is set to 5×10^{18} cm^{-3}. The simulation results can be used for calculating the energy band profile and the overlap between electrons and holes in the quantum wells for both samples.

Figure 4 shows the energy band diagrams and the quasi-Fermi levels of the control and the prestrained samples at 20 mA. A severely tilted potential is found in the quantum wells of the control sample. However, with the prestrained layer, the potential tilt is much reduced. The electric field in the QW is calculated according to the slope of the energy band diagram of the QW. To differentiate the QWs, the QW closest to the n-type layer is defined as QW1. As shown in Table 1, the electric field in each QW of the prestrained sample is smaller than that of the control sample. The electric field in QW1 is 780.2 kV/cm for the control sample and 592.2 kV/cm for the prestrained sample. The variation of the electric field demonstrates the reduced potential tilt or QCSE that arises from the insertion of the prestrained layer, which leads to the higher EL emission peak energy and smaller EL blueshift of the prestrained sample.

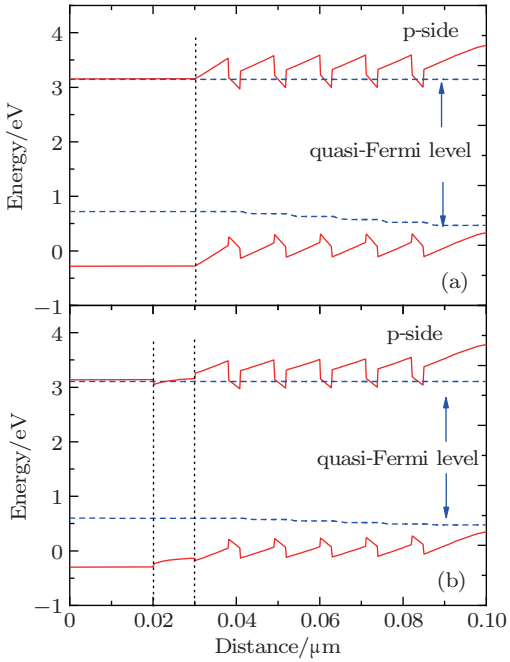


Fig. 4. (color online) Energy band diagrams near the active regions of (a) control sample and (b) prestrained sample at 20 mA.

Table 1. Simulation results of the control and the prestrained samples.

Quantum wells		QW1	QW2	QW3	QW4	QW5
Control sample	electric field/kV·cm^{-1}	780.2	860.8	872.0	874.3	873.8
	overlap/%	50.0	43.8	42.9	42.8	42.8
Prestrained sample	electric field/kV·cm^{-1}	592.2	617.4	618.9	608.2	579.4
	overlap /%	63.5	61.2	60.3	60.5	62.7

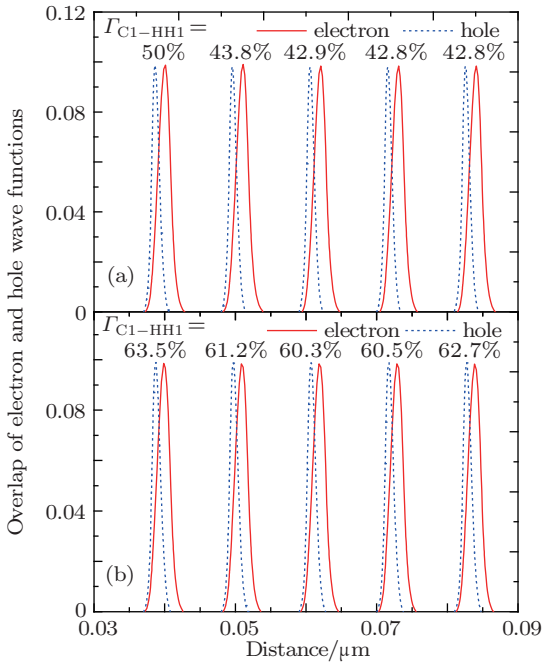


Fig. 5. (color online) Electron and hole wave function overlaps of C1 and HH1 in the five quantum wells of the (a) control sample and (b) prestrained sample at 20 mA.

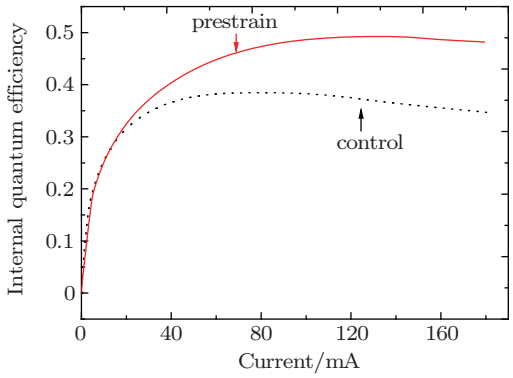


Fig. 6. (color online) Internal quantum efficiency as a function of current for prestrained and control samples.

The electron wave function of the ground conduction subband (C1) and the hole wave function of the uppermost heavy-hole valence subband (HH1) are obtained from the simulation. The transition between these levels plays an important role in the radiative recombination.[17,18] Figures 5(a) and (b) show the electron and the hole wave function spatial distributions and overlaps between C1 and HH1 in the five QWs at 20 mA for the control and the prestrained samples, respectively. The electrons and holes tend to accumulate on different sides due to the QCSE. Because of the prestrain effect, the electron and hole wave function separation is lower in the prestrained sample and the overlap of electron and hole wave functions in QW1 is 50% to 63.5% greater. As shown in Table 1, the overlap of electron and hole wave functions in each QW in the prestrained sample is higher than that of the control sample. The enhanced overlaps improve the radiative recombination rate and lead to a higher emission intensity, which is consistent with the fact that the EL intensity of the prestrained sample at the injection current of 20 mA is increased by 65%. Figure 6 shows the IQE as a function of current for the two samples, and it indicates that the prestrained sample has a better internal quantum efficiency, especially at high currents. It is noteworthy that there is almost no efficiency droop for the prestrained sample in the current range. We believe that the alleviation of the efficiency droop in the prestrained sample is attributable to the higher overlap of electron and hole wave functions under the high injection current.

4. Conclusion

In summary, the influence of the prestrained InGaN interlayer on the emission properties of InGaN/GaN MQWs in LD structures was investigated by comparing two typical samples. A significantly smaller blueshift of the EL peak energy was observed in the prestrained sample when compared with the result of the control sample within the same injection current range (5–50 mA), which indicated a weaker QCSE due to the prestrain effect. Based on the simulation analysis, it was found that the potential tilt was reduced in the prestrained sample. In other words, the electric field in the QWs was smaller and the QCSE was lower in the prestrained sample. Compared with the control sample, the room temperature EL intensity at 20 mA of the prestrained sample was 65% higher and the IQE was 71% greater. In the theoretical simulation results, the prestrained sample exhibited higher light emission efficiency than the control sample due to the enhanced overlap of electron and hole wave functions. The prestrained InGaN interlayer is beneficial to weaken the QCSE, leading to the improvement of the optical properties of blue InGaN/GaN MQW LDs. The present results will provide useful guidance to achieve a high performance LD.

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