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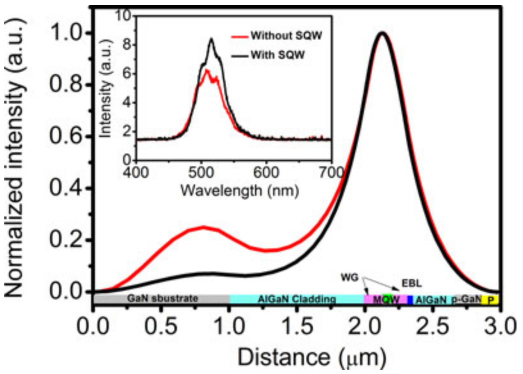

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Performance Enhanced by Inserting an InGaN/GaN Shallower-Quantum Well Layer in InGaN Based Green Laser Diodes

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Abstract: A series of samples with a different InGaN/GaN shallower-quantum well (SQW) interlayer are grown, and their effects on optical properties of InGaN/GaN multi-quantum wells and optical confinement factor of laser diodes (LDs) are investigated. It is found that when an SQW interlayer is inserted below InGaN/GaN green multiquantum wells (GMQWs), the emission intensity of the GMQW active region increases. This is attributed to the reduction of quantum confined stark effect and the V-pit density due to the decreased strain in GMQWs. In addition, we also find that inserting an SQW interlayer theoretically results in a weak leakage of the optical mode for green LDs. Therefore, their performance will be improved.

Index Terms: Green laser diodes (LDs), strain, optical confinement factor.

1. Introduction

Laser display using red, green, and blue (RGB) semiconductor laser diodes (LDs) as light sources is an emerging display technology because it shows larger color gamut and higher color saturation than current television system [1]–[3]. The widest color gamut is obtained with laser wavelengths of 445, 523 and 635 nm and a ratio of 0.6:0.8:1.0 for white (color temperature Tc = 8000 K) [4]. Therefore, the wavelength range from 520 to 530 nm is considered to be optimal for green LDs. In this range, however, it becomes more difficult to achieve by using InGaN/GaN MQWs due to that (1) high dislocation density results from the lattice mismatch between the GaN substrate and

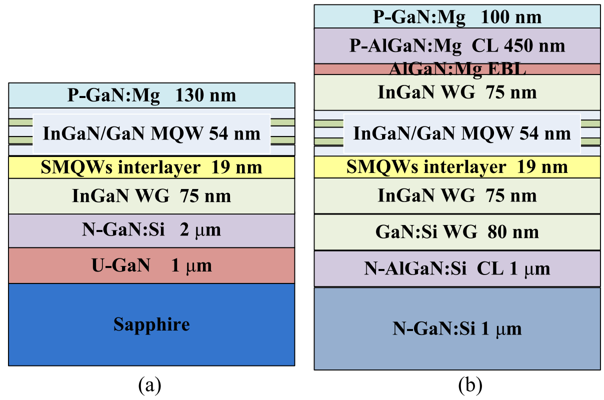

Fig. 1. Schematic structures of LEDs for experiment (a) and LD II for simulation calculation (b)

InGaN active region, leading to a large non-radiative recombination rate [5], (2) strong quantum confined stark effect (QCSE) due to the piezoelectric polarization fields in QWs, leading to the reduction of radiative recombination rate [6], and (3) decreased refractive index contrast between waveguide (WG) layer and AlGaN cladding (CL) layer, leading to the leakage of the optical mode to GaN substrate [7], [8]. All of them will result in the increase of threshold current density and the decrease of slope efficiency for LDs. Therefore, in order to obtain a high performance green LD, some methods should be used to increase the emission efficiency and the optical confinement factor of InGaN/GaN MQW LDs. Over the past few years, since nonpolar (a-plane, m-plane) InGaN QWs are free from QCSE and semipolar (r-plane) InGaN QWs with small QCSE, they are considered to have advantage to fabricate high performance green LDs [9]. However, crystalline defects such as stacking faults [10] and misfit dislocations readily appear in nonpolar and semipolar InGaN QWs, limiting the application of those planes. Therefore, high indium content InGaN/GaN MQWs grown on c-plane GaN substrate is still a more popular technology to fabricate green LDs. In this paper, we focus on improving the performance of c-plane InGaN based green LDs by inserting an InGaN/GaN shallower-quantum well (SQW) layer below activate region. To clearly investigate the influence of SQWs on crystal quality and optical properties of green MQWs (GMQWs), only a thin p-GaN layer (130 nm) is grown above GMQWs instead of upper WG layer and CL layer to fabricate simplified InGaN/GaN MQW LD structures in the experiments, which are called as “LED structures” below, as shown in Fig. 1(a). The performance of the corresponding LD structures (shown in Fig. 1(b)) with an additional SQW interlayer are simulated using the commercial software LASTIP [11], [12]. It is found that both emission intensity and optical confinement factor of InGaN/GaN MQW active region increase when an appropriate InGaN/GaN SQW structure is inserted between lower InGaN WG layer and InGaN/GaN MQW active region. The experimental results and simulation calculations show that the addition of a SQW layer should be an effective method to improve the performance of InGaN based green LDs.

2. Experiments

Four simplified InGaN/GaN MQW LDs (i.e., LEDs) were grown by an AIXTRON 3×2 in close-coupled showerhead reactor on c-plane sapphire substrate. Trimethylgallium, trimethylindium, and ammonia were used as Ga, In, and N precursors, respectively. The schematic structural diagram of LED samples are shown in Fig. 1(a). They consist of a 1-μm thick un-doped GaN layer, a 2-μm thick Si-doped n-type GaN layer, a 75 nm thick $In_{0.05}Ga_{0.95}N$ WG layer, a $19 - 20$ nm InGaN/GaN SQW interlayer, a 2-period InGaN/GaN GMQW active region, and a 130- nm thick Mg-doped p-type GaN layer. The difference of these four samples A, B, C, and D is with or without any InGaN/GaN SQW interlayer, and how is the structure of InGaN/GaN SQW interlayer. The structural parameters of InGaN/GaN SQW interlayer as well as InGaN/GaN MQW active region for samples A, B, C and D are listed in Table 1. In order to check the surface morphology of InGaN/GaN GMQW active region,

TABLE 1
Structural Parameters of Samples A, B, C, and D. There is no InGaN/GaN SMQW Interlayer in Sample A (in 1T Represents the Thickness)

	InGaN/GaN SMQW				Active region		
	In content	QW number	QW T (nm)	QB T (nm)	QW T (nm)	QB T (nm)	In content
LED A	–	–	–	–	2.6	16	30.8%
LED B	~20%	1	3	16	2.6	16	30.8%
LED C	~20%	2	1.5	8	2.6	16	30.8%
LED D	~20%	4	0.75	4	2.6	16	30.8%

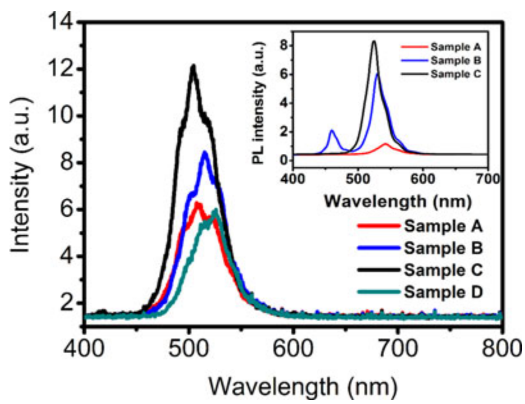

Fig. 2. Room temperature EL spectra of samples A, B, C, and D at the injection current of 10 mA. (Inset) PL spectra of samples A, B and C.

another two InGaN/GaN GMQW samples are grown, their structures are similar to those of LEDs A and B, respectively, but the upper p-GaN layer is not included in the structure. After the epitaxial growth, these 6 samples are characterized by photoluminescence (PL), electroluminescence (EL), X-ray diffraction (XRD), scanning electron microscope (SEM), and atomic force microscope (AFM) measurements to investigate their structural and optical properties.

3. Results and Discussion

Room temperature (RT) EL and PL spectra of samples A, B, C and D are measured and shown in Fig. 2. It is found that all EL spectra at the injection current of 10 mA of these 4 samples have only one peak, which comes from InGaN/GaN GMQWs. It also can be found that the emission intensities of LEDs B and C are much higher than that of LED A, but that of LED D is reduced to be smaller and nearly the same as LED A. It indicates that the microstructure of InGaN/GaN GMQWs may change and the emission efficiency of GMQWs can be improved when a proper InGaN/GaN SQW layer is inserted. For PL spectra (as shown in the inset of Fig. 2), only one peak can be observed in LEDs A and C, but an additional peak centered about 460 nm is also observed in sample B. According to the structure of our samples, this peak is attributed to the InGaN/GaN SQW interlayer where the indium content of InGaN well layer is about 20%. Because the emission efficiency of InGaN well layer decreases with the reduction of well thickness (from 3 to 0.75 nm), a thin quantum well

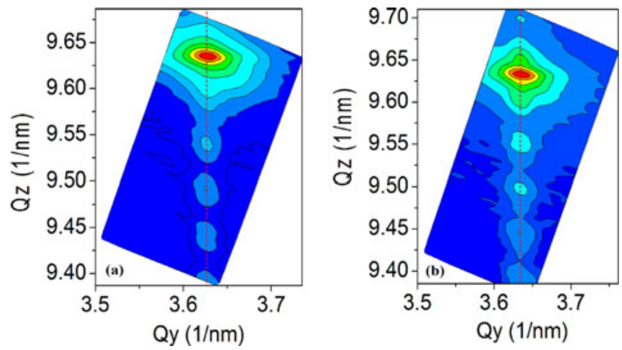

Fig. 3. Asymmetrical (10 − 15) XRD RSM of samples A (a) and B (b)

thickness of InGaN/GaN SQW interlayer will lead to a weak PL emission. In fact, it is not observed in PL spectrum of LED C. In addition, it is also found that the emission intensities of LEDs B and C are much higher than that of LED A. This agrees well with EL measurement.

Actually, the strain in InGaN/GaN GMQWs is very large because the indium content of InGaN well layers for green emission is higher than 30%, and the resulted lattice mismatch is large. In this case, small structural variation of underlayer may have an important influence on the relaxation of InGaN/GaN GMQWs and thus on the emission intensity. In order to check the relaxation degree of GMQWs and find the reason for the different emission efficiencies of samples A, B, C and D, reciprocal space maps (RSMs) of (10 − 15) reflection of all samples are studied first and shown in Fig. 3. It is found that the reciprocal lattice points (RLPs) of InGaN/GaN GMQWs and GaN buffer layer have the same Qy for the all these four samples (the RSMs of LEDs C and D are not shown here). It indicates that the InGaN/GaN GMQWs with or without additional SQW interlayer are all grown coherently on the GaN buffer and no obvious relaxation occurs for all these samples.

Generally, for InGaN/GaN MQWs grown on c-plane substrate, especially in high indium content InGaN materials, the electric field induced by piezoelectric polarization is up to several MV/cm. Such strong polarization fields in InGaN/GaN MQW region result in tilted energy bands, reduced overlap of electron-hole wave function, and lowered carrier recombination rate (i.e., QCSE). Therefore, the optical properties of InGaN/GaN MQWs should be strongly influenced by their stress state. In this section, the EL measurements for samples A, B, C and D under different injection currents are done to investigate the stress state of InGaN/GaN GMQWs active region. The peak wavelength and the integrated intensity derived from the current dependent EL spectra of samples A, B, C and D are shown in Fig. 4(a) and (b). The EL spectra of LEDs B (c) and C (d) under various injection currents are also shown in Fig. 4. It can be seen that the peak wavelength shifts toward shorter wavelength side (a blue-shift), and the integrated EL intensity increases with increasing injection current. It is also shown that a smaller blue-shift is observed for samples B and C, and their EL integrated intensity is larger than other two samples'. As is known, two possible mechanisms may be responsible for the blue-shift of EL peak energy when the injection current increases, i.e., the coulomb screening of the polarization field and the state-filling effect in InGaN QWs, but, generally, coulomb screening of the polarization field dominates at low current range [13]. Thus, the smaller blue-shift of wavelength for samples B and C suggests that the stress in LEDs B and C may be smaller than that of LEDs A and D. Such a smaller stress will result in a weaker QCSE, therefore, a higher emission intensity is obtained for LEDs B and C. However, it is noticed that in difference from LED B, where only one emission peak of InGaN/GaN GMQWs is observed, another peak centered at about 417 nm (marked with peak 2 in Fig. 4(d)) is also observed in EL spectra of LED C when the current injection is larger than 50 mA. It indicates that many holes can go across the InGaN/GaN GMQWs to InGaN/GaN SQW interlayer region and recombine there when the injection current is high. It suggests that this thin barrier layer does not effectively hinder carriers escaping from activate region. In this case, some of the carriers will be wasted away at high injection current for LED C. It is known that the laser diodes must be used under a high injection current. Therefore,

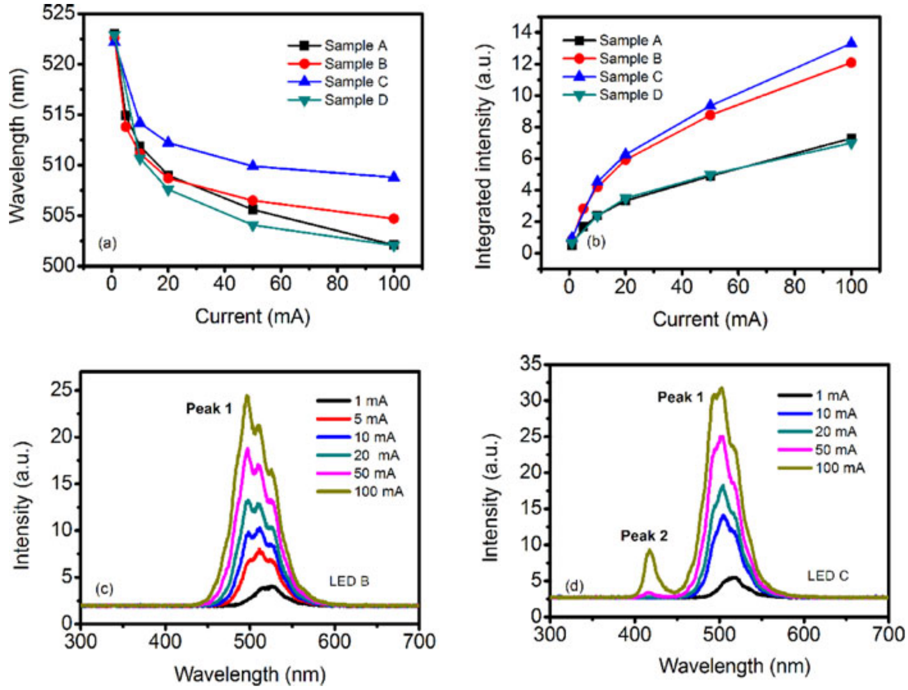

Fig. 4 (a) and (b) Dependences of peak wavelength and integrated intensity of LEDs A, B, C, and D on the increase of injection current, derived from the EL spectra measured under different injection currents. (c) and (d) Dependences of EL spectra on injection currents for LEDs B (c) and C (d).

it seems that a relatively thick period thickness of InGaN/GaN SQW (SQW structure in LED B) is more suitable for green LDs.

In order to further check the structural properties of samples with and without InGaN/GaN SQW interlayer, another two InGaN/GaN MQW samples (named as MQW A and MQW B) are grown, the structure of MQWs A and B are the same as LEDs A and B, respectively, but the p-GaN layer is not grown above the InGaN/GaN GMQW active region. Then both AFM and SEM measurements are done to check their surface morphologies, as shown in Fig. 5. It can be seen that there are some inverted hexagonal pits (V-pits) distributing on the surface of both MQW samples. However, the size and the density of V-pits in these two samples are different for each other. The average size of V-pits in MQW B is much larger than those in MQW A, but their density is smaller. In MQW B, most of V-pits are about 80 nm (as marked with black arrow in Fig. 5(d)), and only a few are about 40 nm (as marked with white arrow in Fig. 5(d). But all of V-pits in MQW A is 20 – 40 nm. It is known that the angel between two opposite pyramid facets of V-pits is nearly 56° [14], the depth of V-pits thus can be calculated according to the diameter of V-pits on the sample surface. It is about 38 – 75 nm in MQW B and 19 – 38 nm in MQW A. Taken the depth of V-pits and the thickness of InGaN/GaN MQWs layer into consideration, we are aware that the V-pits in MQW A are mainly originated from InGaN/GaN GMQWs and those in MQW B are mainly originated from InGaN/GaN SQW. This indicates that the stress in active region of MQW A is larger than that in MQW B because the stress is a main reason for the formation of V-pits in InGaN layer [15]. It agrees well with the results of current dependent EL measurements, as shown in Fig. 4. The reduced stress in active region of MQW B may be attributed to inserting a SQW creating a significant tensile strain in the barrier layer above it that helps in lattice matching for the growth of GQWs. It results in a weak QCSE in the GMQWs, therefore, an increased radiative recombination rate can be obtained in MQW B. In addition, the bottom of V-pits often connects with threading dislocation in the InGaN layers [15], [16], and these threading dislocations often act as non-radiative recombination centers for carriers. However, according to the previous reports [17]–[19], large V-pits can help with preventing injected carriers from moving to these dislocations due to large energy barriers; therefore, the non-radiative

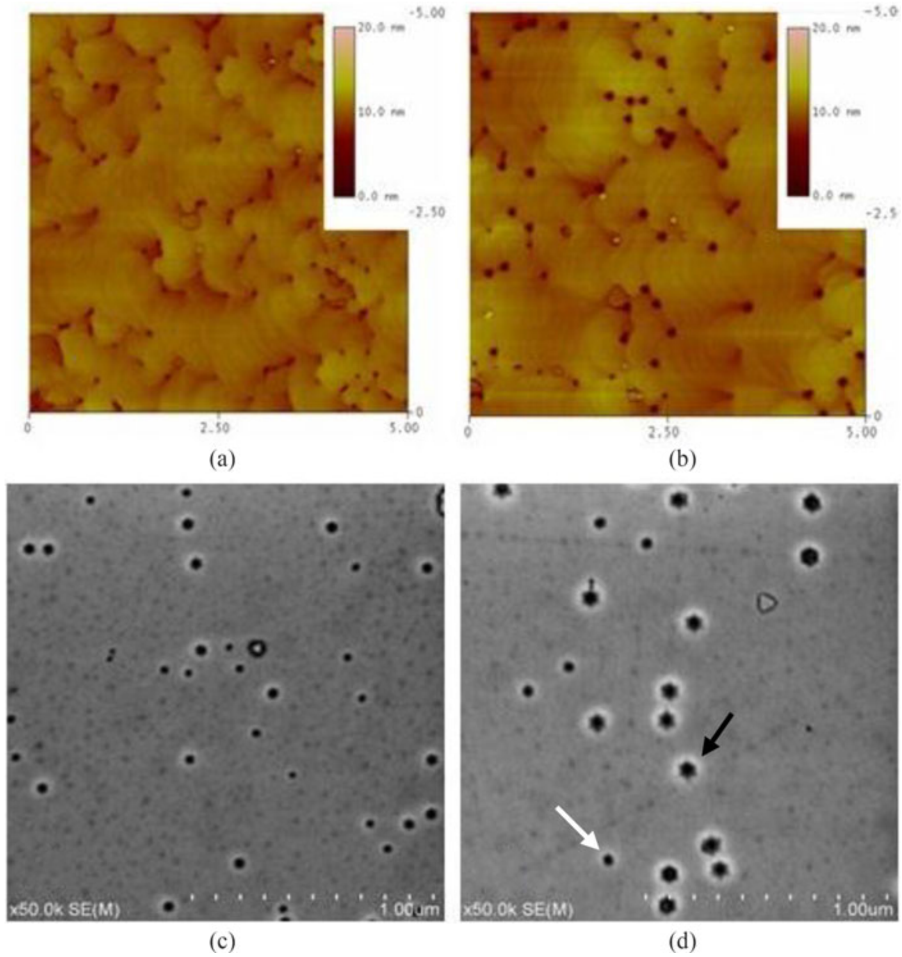

Fig. 5. Top-view AFM and SEM images of the surface morphology for MQW A (a), (c) and MQW B (b), (d).

recombination rate may also decrease in MQW B, which can explain why the emission intensity of LED B is much higher than that of LED A.

Besides a high emission efficiency of GMQWs active region, good optical confinement is needed for high performance LDs. To study the effect of SQW interlayer on optical field distribution and P-I-V behaviors of LDs, LASTIP program is used to simulate the performance of green LDs with and without SQW interlayer, where LD I is the conventional structure without InGaN/GaN SQW interlayer, and LD II is the new structure with an inserted SQW interlayer, composed of 3 nm-thick InGaN QW and 16 nm GaN QB layers, as shown in Fig. 1(b). In this section, the higher emission efficiency of LD II due to the higher crystal quality and lower piezoelectric polarization field (as mentioned above) are not considered during the simulation. One third of the theoretical polarization value is taken in both simulations [20]. The obtained near optical field distribution in LD I and LD II can be seen in Fig. 6, where a light leakage into GaN substrate is clearly visible in LD I, but it becomes very weak after a SQW interlayer is inserted for LD II. This may be attributed to that the effective refractive index contrast between WG layer and CL layer increases in LD II because the inserted SQW interlayer can be regarded as to act as a part of WG layer in LD II. It leads to a higher optical confinement factor and a lower optical loss for LD II. Therefore, the threshold current of LD II, with additional SQW layer, is lower than that of LD I. Actually, if the enhanced emission efficiency of LD II is taken into consideration, we believe the threshold current of LD II will be further decreased.

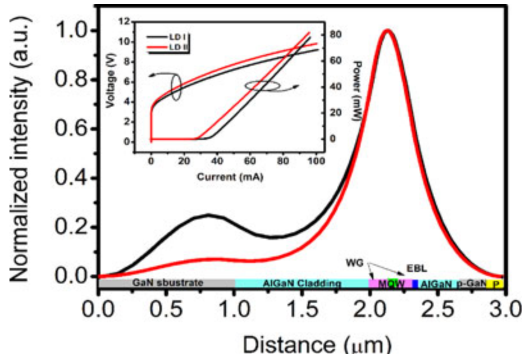

Fig. 6 Simulated near optical field distribution for LD I and LD II. (Inset) Output power and voltage versus injection current for LD I and LD II.

4. Conclusion

A series of samples without and with different SQW interlayers are grown, and their effects on structural and optical properties of InGaN/GaN GMQWs are investigated by using experimental methods. The optical confinement factor and *P*-*I*-*V* behaviors of corresponding LDs with and without additional SQW interlayer are investigated by simulation calculation. It is found that when a SQW interlayer composed of 3 nm thick InGaN QW and 16 nm thick GaN QB layers is inserted below InGaN/GaN GMQWs, the emission efficiency of GMQW active region increases due to the decreased strain and defect density. In addition, after inserting a SQW interlayer, the LD shows a weakened leakage of the optical filed. Therefore, the performance of green LDs will be improved when an additional InGaN/GaN SQW layer is inserted.

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