A dual-blue light-emitting diode based on strain-compensated InGaN–AlGaN/GaN quantum wells*

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A strain-compensated InGaN quantum well (QW) active region employing a tensile AlGaN barrier is analyzed. Its spectral stability and efficiency droop for a dual-blue light-emitting diode (LED) are improved compared with those of the conventional InGaN/GaN QW dual-blue LEDs based on a stacking structure of two $In_{0.18}Ga_{0.82}N$/GaN QWs and two $In_{0.12}Ga_{0.88}N$/GaN QWs on the same sapphire substrate. It is found that the optimal performance is achieved when the Al composition of the strain-compensated AlGaN layer is 0.12 in blue QW and 0.21 in blue-violet QW. The improvement performance can be attributed to the strain-compensated InGaN–AlGaN/GaN QW, which can provide a better carrier confinement and effectively reduce leakage current.

Keywords: InGaN–AlGaN/GaN quantum well, InGaN/GaN quantum well, spectral stability, dual-blue light-emitting diode

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1. Introduction

III–V nitride-based light-emitting diodes (LEDs) have attracted much attention for their applications such as solid-state lighting and backlighting in liquid-crystal displays.[1,2] The $Y_3Al_5O_{12}:Ce^{3+}$ (YAG:Ce) phosphor-converted white LEDs have been widely used in commercial products due to their relatively easy fabrication, low cost, and high brightness.[3] However, this kind of white LED suffers from a low color-rendering index (CRI), and efficiency droop at the high injection current. This efficiency droop phenomenon is influenced by the carrier localization,[4] threading dislocation, and strong built-in electrostatic field caused by the large lattice mismatch between InGaN and GaN in the multiple-quantum well (MQW) active region.[5–7] Many techniques to eliminate the efficiency droop phenomenon have been proposed, such as using newly staggered InGaN quantum well (QW) structure,[8] the δ-AlGaN layer in InGaN QW,[9,10] type-II InGaN–GaNAs QW,[11] InGaN–delta-InN QW,[12] dip-shaped QW,[13] and p-AlInN electron blocking layer.[14] Recently, many studies have shown that the use of the strain compensated layer AlGaN can provide a better carrier confinement and effectively reduce leakage current in the InGaN QW,[15–17] which is important for achieving high performance LEDs.

The current technological target in solid-state lighting is to achieve high color rendering properties without degrading emission efficiency. Our recent study shows that the CRI of a white LED based on the YAG:Ce phosphor conversion can be significantly improved by using dual-blue active layers.[18,19] However, these conventional dual-blue emission peaks are strongly dependent on the injection current due to nonuniform distributions of electrons and holes in the dual-blue active regions.

In this paper, we fabricate two dual-blue wavelength LEDs based on a stacking structure of two $In_{0.18}Ga_{0.82}N$/GaN QWs and two $In_{0.12}Ga_{0.88}N$/GaN QWs on the same sapphire substrate. In order to realize blue and blue-violet light emission with better spectral stability and efficiency, the strain-compensated InGaN–AlGaN/GaN QW structure is utilized in our dual-blue active regions. Specifically, the structure with two $In_{0.18}Ga_{0.82}N$–$Al_{0.12}Ga_{0.88}N$/GaN QWs and two $In_{0.12}Ga_{0.88}N$–$Al_{0.21}Ga_{0.79}N$/GaN QWs on the same sapphire substrate is analyzed theoretically in this study.

2. Experiment

The optical and electrical properties of two kinds of dual-blue LEDs are analyzed and discussed by using the Advanced Physical Model of Semiconductor Devices (APSYS) simulation program,[20] which is capable of dealing with the physical properties of LEDs. Most of the parameters used in this paper are the same as those in Ref. [21]. Other material parameters of the devices used in the simulation can be found in Ref. [22].

The original structure used in this study is grown on (0001)-oriented sapphire substrate by metal-organic chemical vapour deposition (MOCVD) with a Thomas Swan

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close-spaced showerhead reactor. As shown in Fig. 1(a), the conventional InGaN/GaN QW dual-blue LED consists of a GaN buffer layer, a 2-μm-thick undoped GaN layer, a 2-μm-thick Si-doped GaN, a two-period $In_{0.18}Ga_{0.82}N$(3 nm)/GaN(10 nm) QW active region, a two-period $In_{0.12}Ga_{0.88}N$(3 nm)/GaN(10 nm) QW active region, a 15-nm-thick p-type $Al_{0.15}Ga_{0.85}N$ layer as electron blocking layer (EBL), and a 200-nm-thick Mg-doped p-GaN layer. The typical room temperature carrier concentrations of n-GaN and p-GaN are 4×10^{18} cm^{-3} and 5×10^{17} cm^{-3}, respectively. For the strain-compensated InGaN–AlGaN/GaN QW structure, we employ 1-nm-thick strain-compensated AlGaN layer surrounding the InGaN QW which is as thick as the AlGaN layer in Ref. [17]. The Al composition of AlGaN layer is 0.12 for $In_{0.18}Ga_{0.82}N$ QW, and it is 0.21 for $In_{0.12}Ga_{0.88}N$ QW ($x = 0.21$, $y = 0.12$, as seen in Fig. 1(b)), respectively. Note that the total thickness value of the left-hand-side well and the right-hand-side well in the InGaN–AlGaN/GaN QW structure is selected to be the same as that in the conventional InGaN/GaN QW structure and is also fixed at 10 nm. The device geometry is designed into a rectangular shape of 300 μm×300 μm.

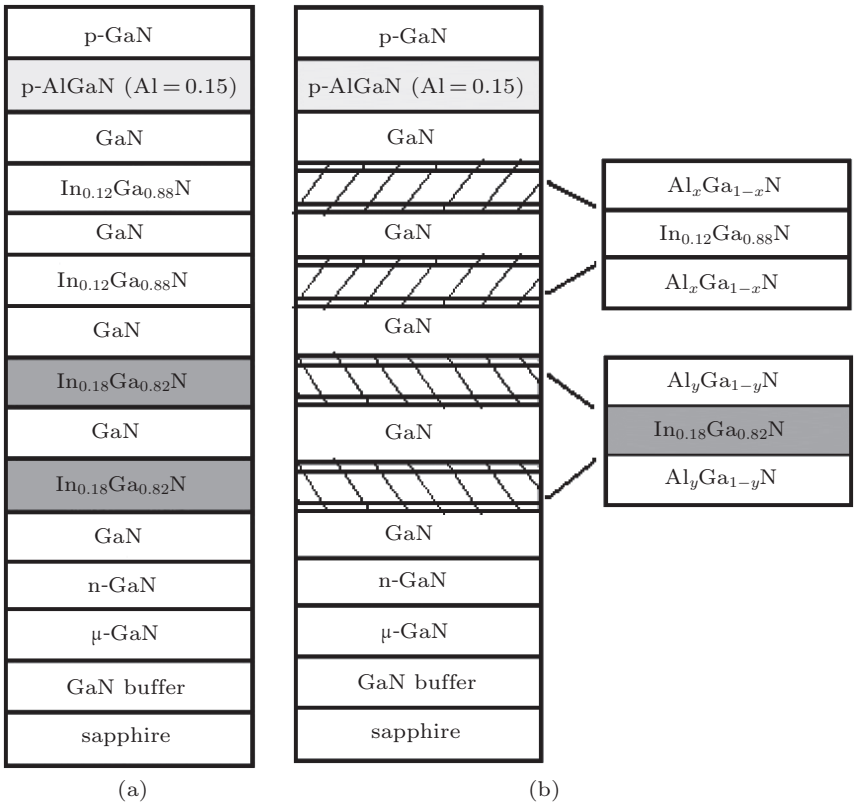


Fig. 1. Schematic structures of a conventional InGaN/GaN QW dual-blue LED (a) and a strain-compensated InGaN–AlGaN/GaN QW dual-blue LED (b).

3. Results and discussion

The insert of Fig. 2(a) demonstrates the experimental electroluminescence (EL) spectra of a traditional InGaN/GaN QW dual-blue LED at different forward currents. Two clear EL peaks are observed in this figure, which originate from the $In_{0.12}Ga_{0.88}N$/GaN QWs and $In_{0.18}Ga_{0.82}N$/GaN QWs, respectively. The blue-violet and blue emission peaks are located at about 440 nm and 470 nm, respectively. At the low injection current, the intensity of blue-violet emission is far stronger than that of blue emission and then the intensity of blue emission increases gradually with injection current increasing. When the injection current reaches 40 mA, the EL intensities of these two emission peaks are almost the same. As the injection current is further increased, the intensity of blue emission becomes larger than that of blue-violet emission. The corresponding intensity ratio of blue-violet light to blue light (L_{BV}/L_B) for InGaN/GaN QW dual-blue LED in a range from 10 mA to 80 mA changes from 4.1 to 0.90, which indicates that carrier distribution of dual-blue active layers with GaN barriers is more nonuniform. Figures 2(a) and 2(b) show the simulated EL spectra of InGaN/GaN LED and InGaN–AlGaN/GaN LED at different forward currents, respectively. In this calculation, some simulation parameters are adjusted in order to make the simulated emission spectra of InGaN/GaN LED consistent with the experimental results. For

the strain-compensated structure, when the dual-blue LED has two-period $In_{0.18}Ga_{0.82}N$–$Al_{0.12}Ga_{0.88}N$/GaN QW and two-period $In_{0.12}Ga_{0.88}N$–$Al_{0.21}Ga_{0.79}N$/GaN QW active regions, the EL intensity ratio of L_{BV}/L_B in a range from 10 mA to 80 mA is almost equal to 1.0, which indicates that carrier distribution of dual-blue active layers employing tensile AlGaN barriers is more uniform than the original structure as shown in Fig. 2(b).

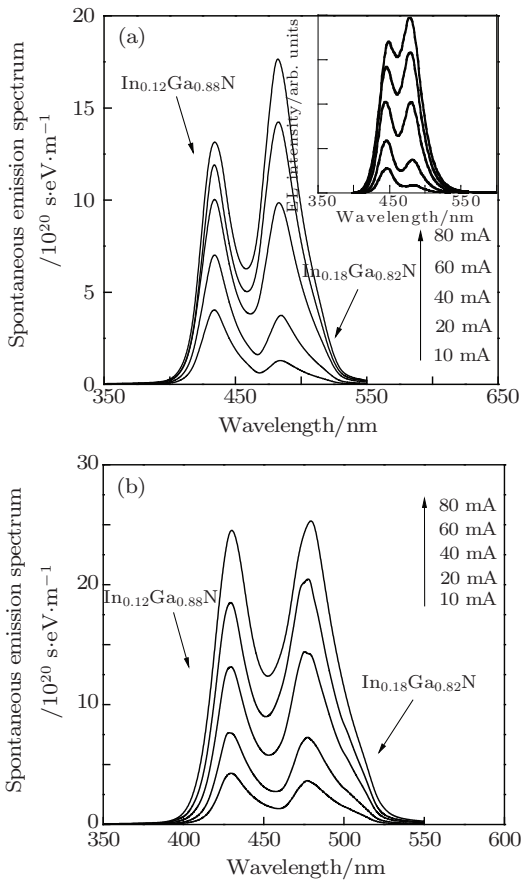


Fig. 2. Simulated EL spectra of InGaN/GaN LED (a) and InGaN–AlGaN/GaN LED (b), with the inset showing the experimental EL spectra of InGaN/GaN QW structure.

Figure 3 shows the calculated band diagrams, quasi-Fermi levels and carrier concentrations of the InGaN/GaN QW structure and the InGaN–AlGaN/GaN QW structure at 20 mA, respectively. It can be observed from Fig. 3(a) that when the LED has GaN barriers, the strong electric field caused by the spontaneous and piezoelectric polarization charges at the interface between the well and barrier layers leads to serious electron current leakage and significant reduction of electron–hole wave functions overlapping due to the lattice mismatch. Thus, low performance can be expected to appear in this structure. On the other hand, for the GaN-based material, a relatively large effective mass and low mobility of holes lead to nonuniform distribution of holes in the dual-blue emitting active layers, resulting in a large number of electrons and holes accumulating in the QW close to the p-side layer. This is consistent with the experimental result that EL emission intensity from the $In_{0.12}Ga_{0.88}N$/GaN QW close to p-GaN side is stronger than that from $In_{0.18}Ga_{0.82}N$/GaN QW near n-GaN side. However, when the thin AlGaN layer is utilized as a QW tensile strain layer surrounding the InGaN QW, the distribution of the carrier improves obviously and the electron and hole distribution become more matched in the whole dual-blue active layers, as seen in Fig. 3(b). Because the utilization of strain-compensated QW structure allows a strain-balance structure, which leads to reductions in strain energy and strain-misfit dislocation density inside the compressively-strained QW, the electronic leakage current is reduced and the hole concentration is enhanced obviously. This is consistent with that the simulated EL spectra that spectrum stability of dual-blue emission becoming better.

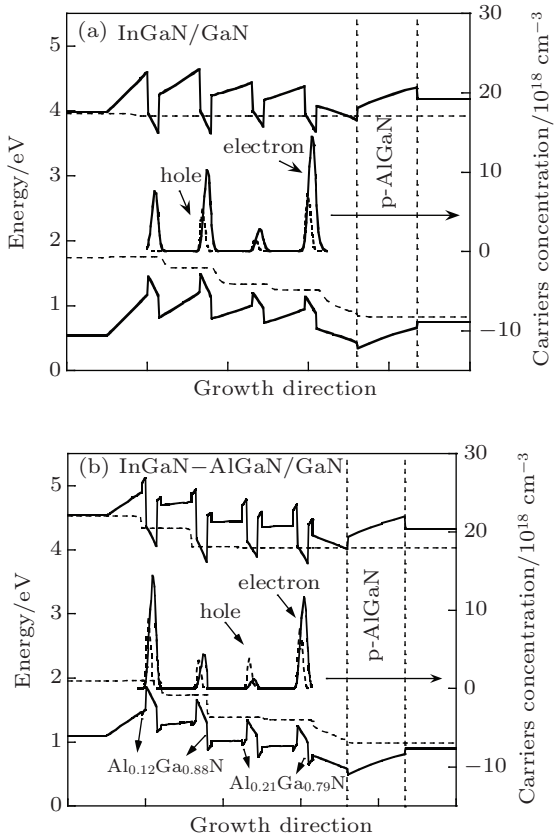


Fig. 3. Band diagrams, quasi-Fermi levels and carrier concentration of InGaN/GaN LED (a) and InGaN–AlGaN/GaN LED (b) at 20 mA.

Figure 4(a) shows that the simulated light output power–current (L–I) performance curve of the original LED is in good agreement with the total extracted light obtained experimentally, which is presented by empty circles. When the thin AlGaN layer is utilized as a QW tensile strain layer surrounding the InGaN QW, InGaN–AlGaN/GaN LED has better lighting efficiency. The light output power of InGaN–AlGaN/GaN LED at 80 mA is improved by a factor of 1.75 as compared with that of InGaN/GaN LED. It is noteworthy that there is almost no obvious efficiency droop for InGaN–AlGaN/GaN

LED and the issue for serious efficiency droop of the original LED will be mitigated consequently as shown in Fig. 4(b). Because of the advantages in carrier confinement and electron blocking, the performance of the InGaN–AlGaN/GaN QW structure is expected to be superior to that of the InGaN/GaN QW structure.

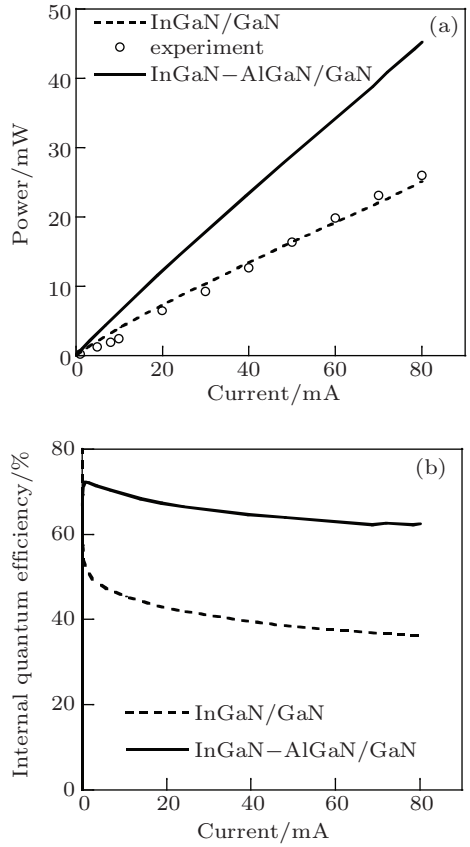


Fig. 4. (a) *L–I* curves of InGaN/GaN and InGaN–AlGaN/GaN dual-blue LEDs (Experimental data are presented by empty circles) and (b) curves of internal quantum efficiency versus current for the corresponding LEDs.

Figure 5 shows the curves of EL intensity ratio of L_{BV}/L_B versus injection current for the strain-compensated InGaN–AlGaN/GaN LED with variant Al composition (x, y). Four groups of Al composition (x, y) of strain-compensated AlGaN layers are listed in Fig. 5, and they are (0.18, 0.08), (0.20, 0.10), (0.21, 0.12), and (0.25, 0.15). When x is 0.25 and y is 0.15, L_{BV}/L_B will be more than 1, which implies that the EL intensity of blue-violet light is stronger than that of blue light, especially at the low injection current. On the contrary, when (x, y) are (0.18, 0.08) and (x, y) are (0.20, 0.10), respectively, both the EL intensity of blue-violet light are less than EL intensity of blue light, i.e., $L_{BV}/L_B < 1$. However, when (x, y) are equal to (0.21, 0.12), L_{BV}/L_B equals 1. In conclusion, when the Al compositions of strain-compensated AlGaN layer surrounding the blue-volet QW and blue QW are 0.21 and 0.12, respectively, the InGaN–AlGaN/GaN dual-blue LED has better spectral stability. The relevant epitaxial growth and chip fabrication technologies are underway in our laboratory to realize dual-blue LED with InGaN–AlGaN/GaN QW.

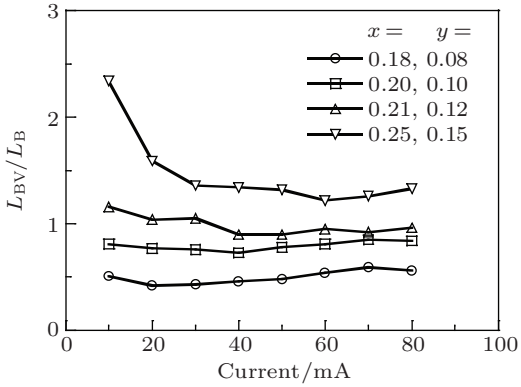


Fig. 5. Curves of EL intensity ratio of L_{BV}/L_B versus injection current for the strain-compensated InGaN–AlGaN/GaN LED with variant Al composition.

4. Conclusions

In the present study, when strain-compensated $Al_{0.12}Ga_{0.88}N$ layer and $Al_{0.21}Ga_{0.79}N$ layer are employed as the $In_{0.18}Ga_{0.82}N$ QW and the $In_{0.12}Ga_{0.88}N$ QW barrier layers, respectively, the electron and hole distribution become more matched in the whole dual-blue active layers. The corresponding dual-blue LED has better spectral stability and no obvious efficiency droop. The improved performance is attributed mainly to the better carrier confinement and the reduction in electronic leakage current due to the employment of the thin AlGaN tensile strain layer surrounding the InGaN quantum well.

References

[1] Schubert E F and Kim J K 2005 *Science* **308** 1274
[2] Pimputkar S, Speck J S, Denbaars S P and Nakamura S 2009 *Nat. Photonics* **3** 180
[3] Zukauskas A, Vaicekauskas R, Ivanauskas F, Gaska R and Shur M S 2002 *Appl. Phys. Lett.* **80** 234
[4] Wang J X, Wang L, Zhao W, Hao Z B and Luo Y 2010 *Appl. Phys. Lett.* **97** 201112
[5] Kim M H, Schubert M F, Dai Q, Kim J K and Schubert E F 2007 *Appl. Phys. Lett.* **91** 183507
[6] Kuo Y K, Yen S H, Tsai M C and Liou B T 2007 *Proc. SPIE* **6669** 66691I-1
[7] Lee W, Kim M H, Zhu D, Noemaun A N, Kim J K and Schubert E F 2010 *J. Appl. Phys.* **107** 063102
[8] Arif R A, Ee Y K and Tansu N 2007 *Appl. Phys. Lett.* **91** 091110
[9] Park J and Kawakami Y 2006 *Appl. Phys. Lett.* **88** 202107
[10] Park S H, Park J and Yoon E 2007 *Appl. Phys. Lett.* **90** 023508
[11] Arif R A, Zhao H and Tansu N 2008 *Appl. Phys. Lett.* **92** 011104
[12] Zhao H, Liu G and Tansu N 2010 *Appl. Phys. Lett.* **97** 131114
[13] Lu T P, Li S T, Zhang K, Liu C, Xiao G W, Zhou Y G, Zheng S W, Yin Y A, Wu L J, Wang H L and Yang X D 2011 *Chin. Phys.* B **20** 108504
[14] Lu T P, Li S T, Zhang K, Liu C, Xiao G W, Zhou Y G, Zheng S W, Yin Y A, Wu L J, Wang H L and Yang X D 2011 *Chin. Phys.* B **20** 098503
[15] Zhao H, Arif R A, Ee Y K and Tansu N 2007 *Optical and Quantum Electronics* **39** 12
[16] Zhao H, Arif R A, Ee Y K and Tansu N 2008 *Proc. SPIE* **6889** 688903
[17] Tsai C L, Liu G S, Lee Y S and Fan G C 2010 *J Electrochem. Soc.* **157** H260
[18] Chen X W, Zhang Y, Li S T, Yan Q R, Zheng S W, He M and Fan G H 2011 *Phys. Status Solidi* A **208** 1972
[19] Yan Q R, Zhang Y, Li S T, Yan Q A, Shi P P, Niu Q L, He M, Li G P and Li J R 2012 *Opt. Lett.* **37** 1556
[20] APSYS by Crosslight Software Inc. Burnaby Canada (http://www.crosslight.com)
[21] Kuo Y K, Chang J Y, Tsai M C and Yen S H 2009 *Appl. Phys. Lett.* **95** 011116
[22] Vurgaftman I and Meyer J R 2003 *J. Appl. Phys.* **94** 3675