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Improved performance of InGaN light-emitting diodes with a novel sawtooth-shaped electron blocking layer*

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A sawtooth-shaped electron blocking layer is proposed to improve the performance of light-emitting diodes (LEDs). The energy band diagram, the electrostatic field in the quantum well, the carrier concentration, the electron leakage, and the internal quantum efficiency are systematically studied. The simulation results show that the LED with a sawtooth-shaped electron blocking layer possesses higher output power and a smaller efficiency droop than the LED with a conventional AlGaN electron blocking layer, which is because the electron confinement is enhanced and the hole injection efficiency is improved by the appropriately modified electron blocking layer energy band.

Keywords: light-emitting diodes, efficiency droop, electron blocking layer

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1. Introduction

III-nitride-based multiple quantum well light-emitting diodes (MQW LEDs) have attracted considerable attention due to their applications in display back lighting, communications, medical services, signage, energy-efficient solid-state lighting, etc.[1–5] However, these devices all suffer from a rapid reduction in emission efficiency with the increase in injection current. This phenomenon, called efficiency droop, is a serious restriction on high brightness and high power applications of LEDs,[3,4] and must be solved for devices operating at high injection currents. The optical performances of InGaN-based LEDs can be largely weakened by several mechanisms, including carrier leakage due to the polarization effect,[3–7] Auger recombination,[8] current injection efficiency,[9] lack of hole injection,[10–12] the self-heating effect,[13] etc. Up to now, this issue has been under investigation. For InGaN-based LEDs, however, electron current leakage and poor hole injection efficiency are usually identified to be the major reasons for the efficiency droop issue.[3–7,10–12]

For the efficiency of electron confinement, the electron blocking layer (EBL) plays an important role in MQW LEDs. Unfortunately, the conventional p-type AlGaN EBL cannot usually block the electron in the active region effectively due to the large band-bending caused by the polarization field.[5,7] It also works as a potential obstacle barrier to preclude holes from being injected into the quantum wells (QWs).[3,11] Several EBL designs are proposed to alleviate the above problems, including an InAlN EBL,[7,14,15] AlGaInN EBL,[16] n-type AlGaN EBL,[17] AlGaN/GaN superlattice EBL,[18] and removing the AlGaN EBL.[19] However, there are still some limitations of these designs such as the technical challenges in growing high-quality crystals due to very different optimum growth temperatures and pressures[7,16] or a reduction in the electron confinement efficiency.[17,19] In this work, we propose a novel sawtooth-shaped EBL with different spaces between the two teeth. With this novel design, the efficiency of electron confinement and hole injection are greatly improved.

2. Device structures

The LED with a conventional EBL structure used as a reference was grown on a *c*-plane sapphire substrate, followed by a 50 nm thick undoped GaN buffer layer. A 3-μm thick n-type GaN layer was then prepared (n-doping $= 5\times10^{18}$ cm^{-3}) before the growth of InGaN/GaN MQWs. The active region consists of five 3-nm thick $In_{0.13}Ga_{0.87}N$ quantum wells, separated by six 10-nm thick GaN barriers. On the top of the active region was a 30-nm thick p-type $Al_{0.15}Ga_{0.85}N$ EBL (p-doping $= 1.2\times10^{18}$ cm^{-3}) followed by a 250-nm thick p-type GaN cap layer (p-doping $= 1.2\times10^{18}$ cm^{-3}). The geometric size of the device was 300 μm × 300 μm. For comparison, three LEDs with sawtooth-shaped EBLs were designed. The redesigned LEDs are identical to the conventional ones except that their AlGaN EBLs were replaced, respectively, by 30-nm thick p-type $Al_xGa_{1-x}N$-GaN-$Al_xGa_{1-x}N$ EBLs (with x linearly graded from 0 to 0.15 in the growth direction, p-doping $= 1.2\times10^{18}$ cm^{-3}). The thickness of the middle GaN layer was δ, whose values are set to be 15 nm, 10 nm, and 5 nm for the three redesigned LEDs, respectively. The thickness of each $Al_xGa_{1-x}N$ layer is $(30-\delta)/2$. Figure 1 shows a

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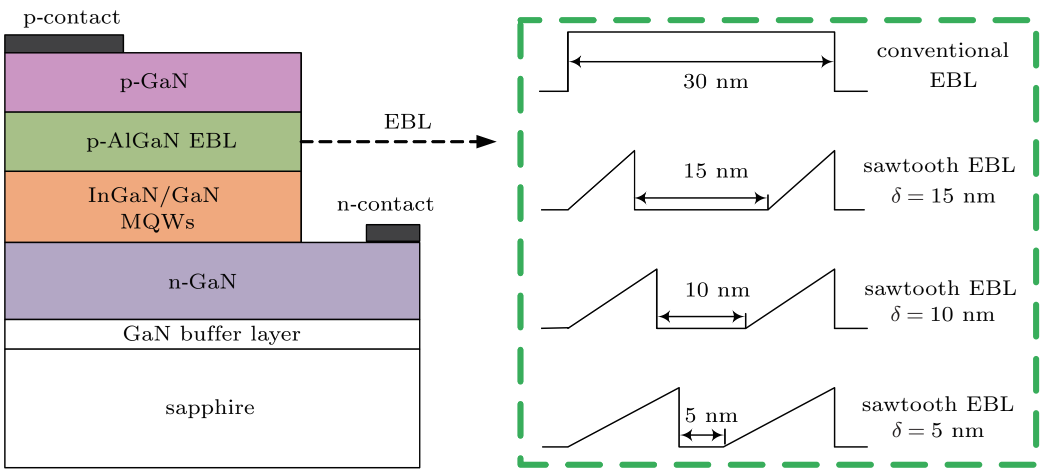

Fig. 1. (color online) Schematic diagram of the LED (left) and the schematic energy band diagrams of the four EBLs (right).

schematic diagram of the conventional LED structure. The schematic energy band diagrams of the four EBLs are plotted on the right-hand side of the figure. It is noted that the energy band diagrams of the redesigned EBLs are sawtooth-shaped. The optical and electrical properties of the LEDs were investigated numerically with the APSYS simulation program, which was developed by Crosslight Software Inc.[20] The method developed by Fiorentini *et al.*[21] was used to calculate the polarization-induced charges at the interfaces, and the operation temperature was assumed to be 300 K. The internal absorption within the LED device and the light extraction efficiency were assumed to be 500 m^{-1} and 78%, respectively. The other material parameters of the semiconductors used in the simulation can be found in Ref. [22].

3. Analysis and discussion

Figure 2 shows the conduction energy band diagrams and quasi-Fermi levels of the conventional EBL and sawtooth-shaped EBL LEDs at 180 mA. As indicated in Fig. 2(a), the energy band at the interface of last-barrier/EBL is seriously downward-bending due to the polarization field, which leads

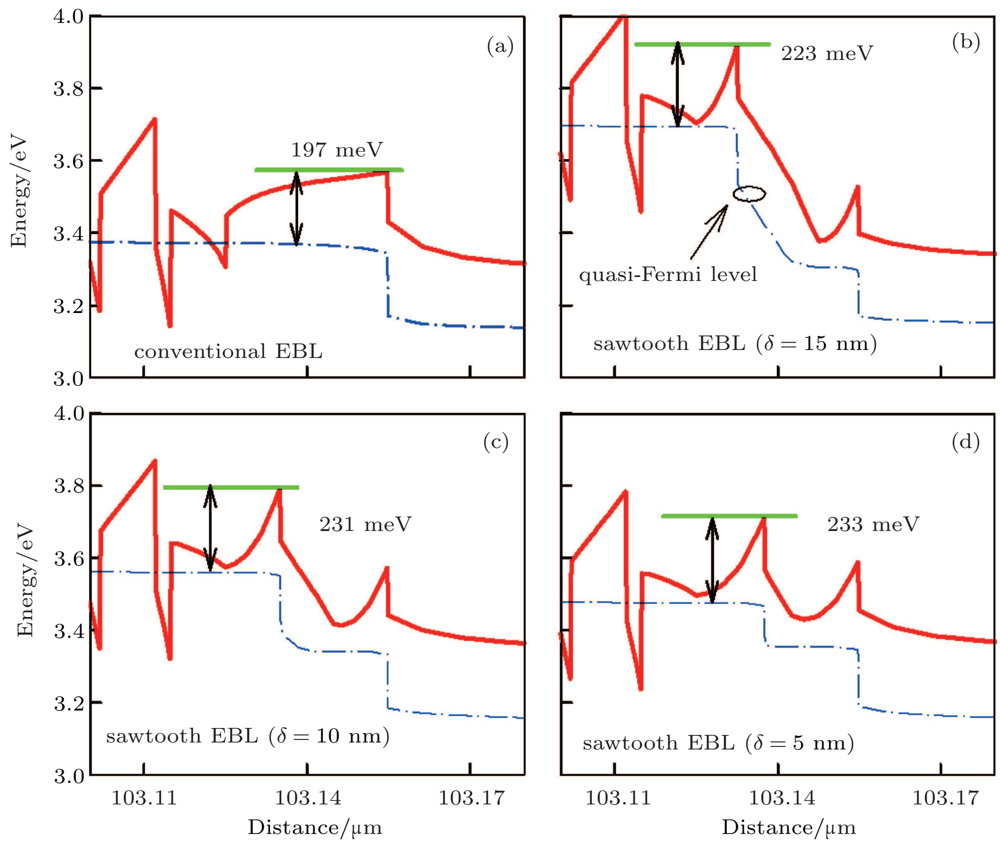

Fig. 2. (color online) Conduction energy band diagrams for LEDs with (a) conventional EBL, (b) sawtooth EBL ($\delta = 15$ nm), (c) sawtooth EBL ($\delta = 10$ nm), and (d) sawtooth EBL ($\delta = 5$ nm) at an injection current of 180 mA.

to a low effective barrier height (defined as the potential difference between the maximum energy of the EBL and the quasi-Fermi level in front of the EBL) of the EBL. Thus, it causes the electron leakage to overflow from the active region to the p-layers easily. There exists a low energy point where the energy of the conduction band is below the quasi-Fermi level at the last-barrier/EBL interface. However, as shown in Figs. 2(b)– 2(d), when the conventional EBL is replaced by the sawtooth-shaped EBL, the problem in the conventional LED is improved, and the low energy point is lifted up to the position above the quasi-Fermi level. The effective barrier height of the EBL increases from 197 meV to 223 meV for the sawtooth EBL with $\delta = 15$ nm compared with the conventional one. It is also found that the effective barrier height can further increase with δ decreasing. Consequently, the enhanced effective barrier height of the EBL can improve the efficiency of electron confinement and make more electrons stay in the MQWs. Because the electrons overflowing from the MQWs can capture holes before they reach the active region, thereby weakening the hole injection efficiency into the QWs. Thus, when the electron leakage current is decreased, the efficiency of the holes injected into the active region can be enhanced because the holes that recombine with the leaked electrons outside the MQWs are diminished.

Figure 3 plots the valence energy band diagrams near the EBL of the LEDs at 180 mA. It is obvious that there is a strong polarization-induced downward band-bending at the last-barrier/EBL interface, causing the EBL to work as a potential for hole injection into the active region. The effective barrier height for the hole in the valence band of the conventional EBL is much greater than that of the sawtooth one, which hinders the holes from being injected into the MQWs. When the conventional EBL is replaced by the sawtooth EBL, the effective barrier height for the hole decreases significantly from 292 meV to 254 meV. Moreover, with δ decreasing, the effective barrier height can further decrease. Therefore, the sawtooth EBL retains better performance due to improved hole injection. Meanwhile, the increased hole concentration leads to the fact that more electrons can be recombined in the MQWs, and thus the electron leakage can be reduced in turn.

These phenomena can be verified by the electrostatic fields. Figure 4 shows the electrostatic fields near the last-barrier/EBL interface and in the active region of the LED at 180 mA. It is evident that the conventional EBL LED possesses the strongest electrostatic field near the last-barrier/EBL interface because of the severe lattice mismatch between the last GaN barrier and the AlGaN EBL, which leads to the band-bending (see Figs. 2(a) and 3(a)). Due to higher quality lattice-match by replacing the conventional EBL with sawtooth-shaped one ($\delta = 15$ nm), the surface charge density significantly decreases and thus the electrostatic field is markedly

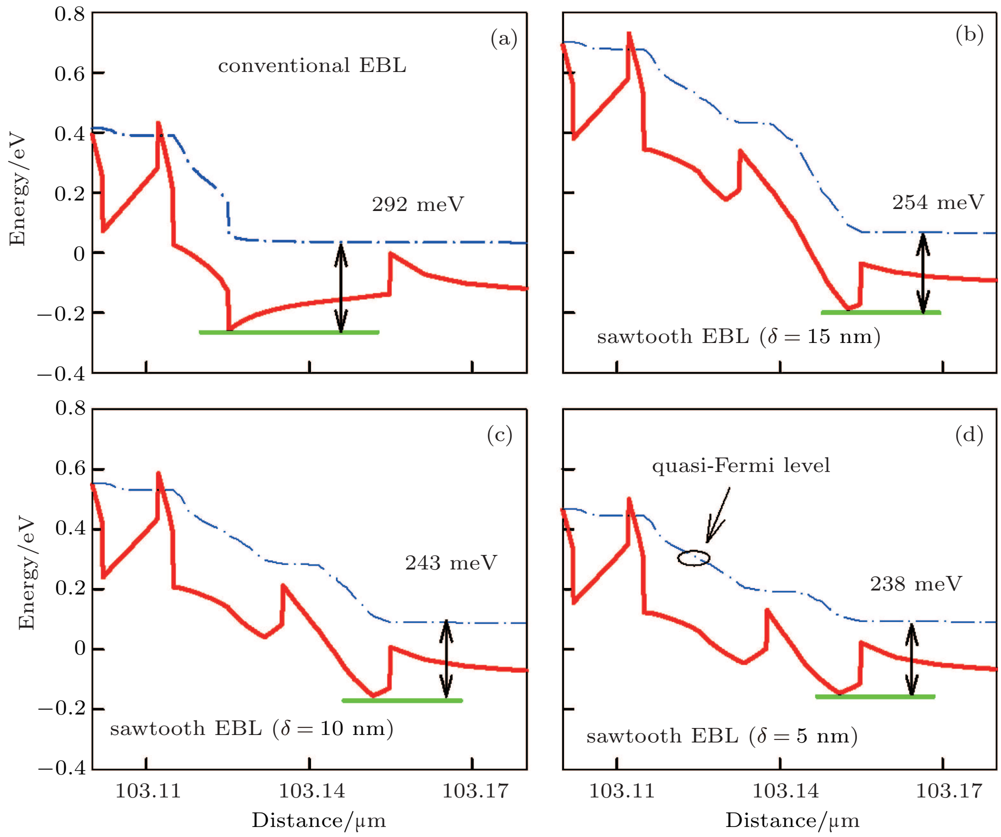

Fig. 3. (color online) Valence energy band diagrams for LEDs with (a) a conventional EBL, (b) a sawtooth EBL ($\delta = 15$ nm), (c) a sawtooth EBL ($\delta = 10$ nm), and (d) a sawtooth EBL ($\delta = 5$ nm) at an injection current of 180 mA.

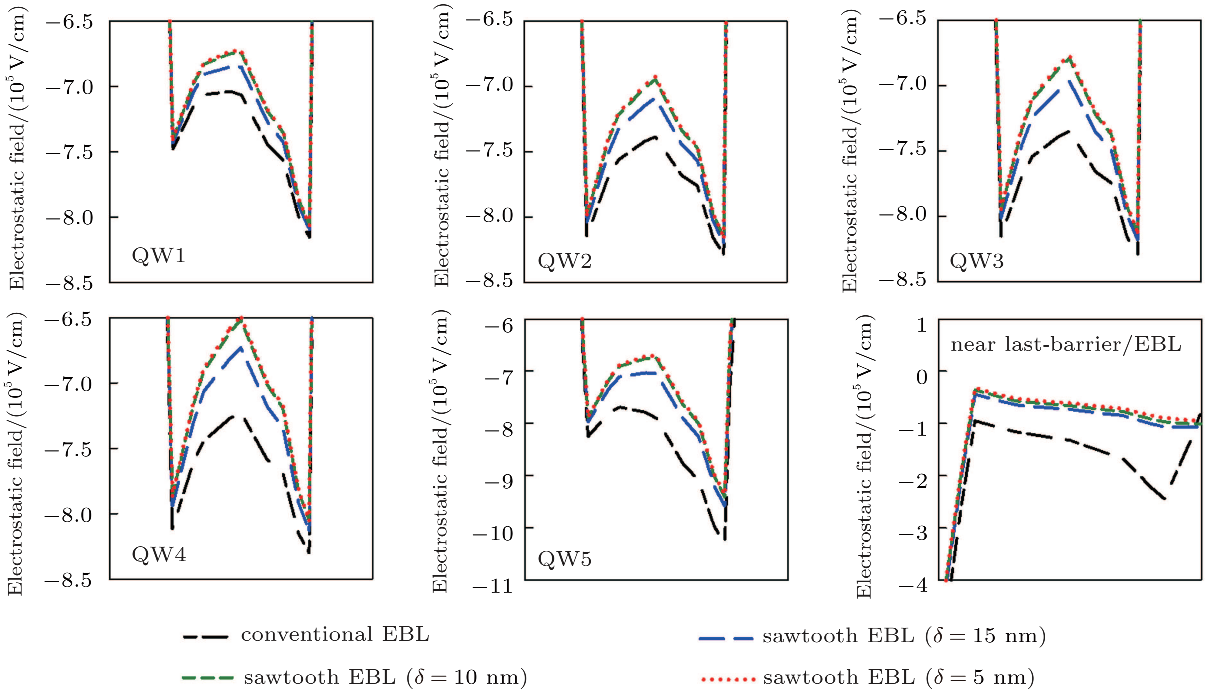

Fig. 4. (color online) Electrostatic fields in the five QWs and near last-barrier/EBL interfaces of the four LEDs at 180 mA.

alleviated. It can further decrease the degree of polarization-induced band-bending by reducing δ from 15 nm to 5 nm. The reduced electrostatic field will increase the effective barrier height of the conduction band and reduce the potential height of the effective barrier of the valence band for the EBL, leading to enhanced electron confinement efficiency and hole injection. As a result, the sawtooth EBL LED with $\delta = 5$ nm will provide the best effective confinement ability, so electrons overflowing into the p-type layer are greatly diminished and holes are efficiently injected into the MQWs, which results in the lowest electron leakage (see Fig. 5). On the other hand, the electrostatic field in each QW decreases when the sawtooth EBLs are used, which in turn leads to the enhancement in radiative recombination rate due to the improved quantum confined Stark effect (QCSE). Moreover, the electrostatic field in the QW will decrease when the value of δ is smaller.

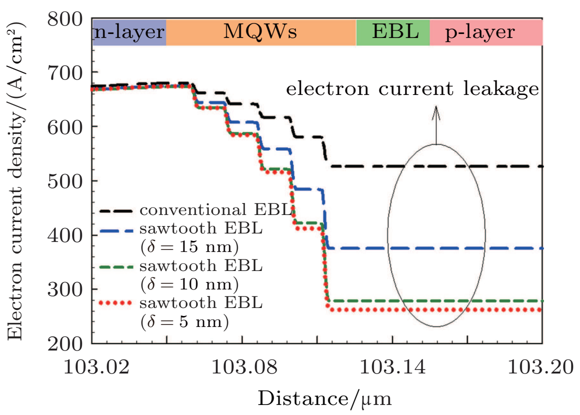

Fig. 5. (color online) Electron current leakage profiles near the active region for the four LEDs at 180 mA.

The better electron confinement ability of the sawtooth EBLs can be justified by the electron current leakage profile near the active region, which is plotted in Fig. 5. The electrons are injected from n-layers into the MQWs and then recombine with holes, which results in the decrease in electron current density along the transportation distance. The electron current overflowing from the MQWs is viewed as current leakage. As shown in Fig. 5, it is apparent that the electron leakage overflow across the EBL into the p-layer of the conventional LED is quite serious. When the sawtooth EBLs are employed, the electron leakage is substantially reduced due to the better electron confinement efficiency. As also indicated in Fig. 5, the electron leakage can be further suppressed with δ decreasing. Consequently, more electrons will stay in the active region to recombine with holes. This is consistent with the improved modified energy band diagrams in Figs. 2 and 3, which can be further justified by comparing the electron and hole concentrations in the MQWs, as shown in Figs. 6 and 7.

Figures 6 and 7 show the carrier concentrations in the active region for the four LEDs at 180 mA. Note that the

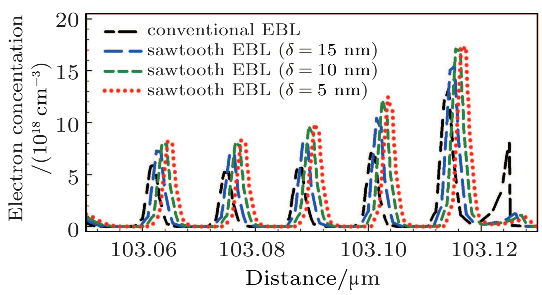

Fig. 6. (color online) Electron concentrations within the active regions for the four LEDs at 180 mA.

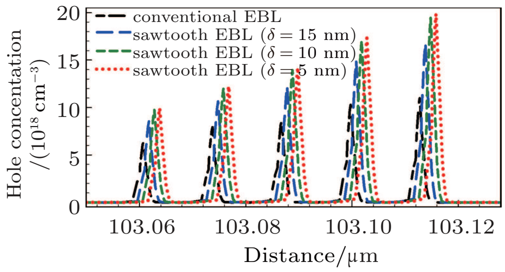

Fig. 7. (color online) Hole concentrations within the active regions for the four LEDs at 180 mA.

horizontal positions of the LEDs with a sawtooth EBL are shifted slightly for better observation. As shown in Fig. 6, the accumulation of electrons at the interface of the last-barrier/EBL is observed as expected, indicating the large electron leakage due to the severe electrostatic field near the interface (see Fig. 4). However, when the sawtooth EBLs are used, the accumulated electrons are diminished, justifying the improved efficiency of electron confinement. It is evident in Fig. 6 that the electron concentration of the sawtooth EBL LEDs is obviously increased compared with that of the conventional one. It is also observed that the hole concentrations of the three sawtooth EBL LEDs also increase. For the LED with a sawtooth EBL ($\delta = 5$ nm), the electron and hole concentrations in the MQWs are enhanced by factors of 1.5 and 1.7, respectively, compared with those in the conventional LEDs. As a result, the radiative recombination rates within the active region can be improved due to the above carrier concentration advantages, as shown in Fig. 8.

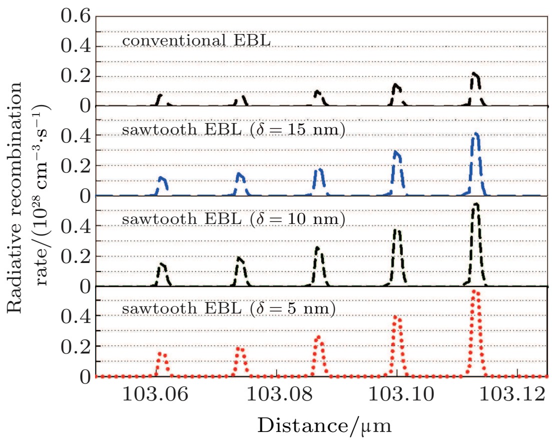

Fig. 8. (color online) Radiative recombination rates within the active region for the four LEDs at 180 mA.

Figure 9 shows the curves of internal quantum efficiency (IQE) and light output power for the LEDs with the conventional and sawtooth EBLs versus injection current. It is obvious that the IQE and output power are dramatically enhanced in the LEDs with sawtooth EBLs compared with those in the conventional LEDs. Moreover, the performance of the LED becomes better with decreasing δ, and the sawtooth EBL LED with $\delta = 5$ nm has a highest IQE and light output power at 180 mA. If the degree of efficiency droop ζ is defined as $\zeta = (IQE_{\max} - IQE_{\min})/IQE_{\max}$, then the conventional EBL LED exhibits a serious efficiency droop with $\zeta = 55.2\%$. The value of ζ decreases to 35.4% for the sawtooth LED ($\delta = 5$ nm), and the enhancement of IQE leads to the improvement in output power. The ratio of improved output power for the LED with a sawtooth EBL ($\delta = 5$ nm) is 2.69 at 180 mA compared with that for the conventional LED. The sawtooth LED with $\delta = 5$ nm is the best option for high-power applications in the three LED structures.

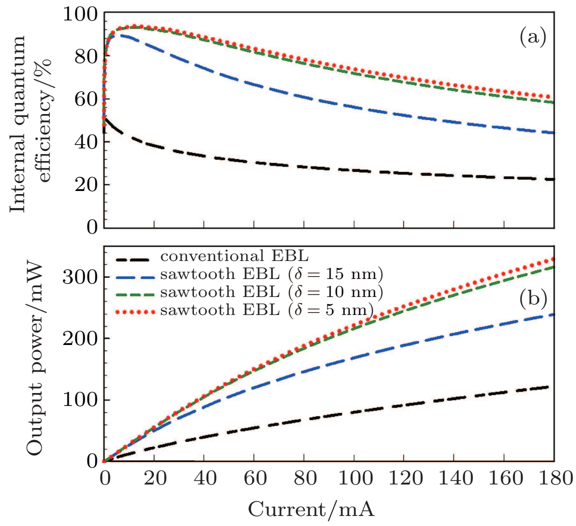

Fig. 9. (color online) Curves of (a) internal quantum efficiency and (b) light output power versus injection current for the four LEDs.

4. Conclusions

In this paper, InGaN/GaN MQW LEDs with conventional EBLs and sawtooth-shaped EBLs with different δ values are investigated numerically. When the conventional EBL is replaced by a sawtooth-shaped one, the effective barrier height of the conduction band is increased and the barrier obstacle in the valence band for holes is mitigated due to the correctly modified energy band of the EBL. Consequently, the properties of the EBL can be improved, and thus the electron confinement is enhanced and more holes can be transported from the p-type region into the active region. This effect prevents electron leakage and improves the radiative recombination rate in the quantum well, leading to a significant improvement in IQE and light output power. The LED with a sawtooth EBL ($\delta = 5$ nm) has the best performance.

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