

# Advantages of the Blue InGaN/GaN Light-Emitting Diodes with an AlGaIn/GaN/AlGaIn Quantum Well Structured Electron Blocking Layer

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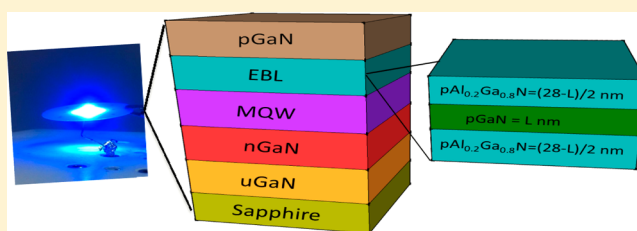
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## Supporting Information

**ABSTRACT:** InGaN/GaN light-emitting diodes (LEDs) with p-(AlGaIn/GaN/AlGaIn) quantum well structured electron blocking layer (QWEBL) are designed and grown by a metal–organic chemical-vapor deposition (MOCVD) system. The proposed QWEBL LED structure, in which a p-GaN QW layer is inserted in the p-AlGaIn electron blocking layer, not only leads to an improved hole injection but also reduces the electron leakage, thus enhancing the radiative recombination rates across the active region. Consequently, the light output power was enhanced by 10% for the QWEBL LED at a current density of 35 A/cm<sup>2</sup>. The efficiency droop of the optimized device was reduced to 16%. This is much smaller than that of the conventional p-AlGaIn electron blocking layer LED, which is 31%.

**KEYWORDS:** GaN, LED, QW, EBL, MOCVD



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For InGaN/GaN light-emitting diodes (LEDs) working as the light source for artificial lighting, a high operating current density is necessary to generate sufficient light output power. However, at high current densities an efficiency droop is often observed, and many efforts have been made to suppress the efficiency droop.<sup>1</sup> A p-AlGaIn electron blocking layer (EBL), as one of the basic LED structure layers, is typically applied to fulfill this function. However, it has been found that although the p-AlGaIn EBL is able to reduce the overflow of the electrons from the active region to the p-GaN layer, it also retards the hole injection from the p-GaN layer to the active region.<sup>2</sup> Many variants based on the p-AlGaIn EBL have been proposed and realized, which have greatly enhanced the optical power and reduced the efficiency droop under high current intensity. These approaches include p-AlGaIn EBL with graded Al composition,<sup>3</sup> AlGaIn/GaN superlattice EBL,<sup>4</sup> AlInGaIn quaternary EBL,<sup>5</sup> and AlInN EBL.<sup>6</sup> In practice, the graded Al composition EBL and the superlattice EBL are not easy to be realized since they need very precise control of the composition and the thickness of the EBL layer.<sup>7</sup> For quaternary AlInGaIn- and AlInN-type EBLs, due to the large difference of AlN and InN in bonding strength and thermal property, the growth has to be conducted at a low temperature with N<sub>2</sub> as carrier gas. Therefore, the growth conditions are difficult to control and the material quality is often compromised. Moreover, the degraded

quality of the EBL will also lead to the degradation of the quality of the subsequent p-GaN layer.<sup>8</sup> To simplify the growth process, guarantee a high crystal quality, and maintain the electron blocking function of the EBL, Xia et al. have theoretically demonstrated the advantages of the p-type AlGaIn/GaN/AlGaIn (AGA) EBL with an inserted p-GaN layer thicker than 4 nm.<sup>9</sup> However, there is no experimental study performed to prove their concept.

In this work, different from previously studied structures, we initiate a new type of AGA EBL with a thin p-GaN layer of thickness less than 4 nm: the thin p-GaN layer serves as a quantum well (QW), and the AlGaIn layers with an Al composition of 20% were regarded as the barriers. Therefore, the proposed architecture is a quantum well structured EBL (QWEBL). The improvements in electron confinement and hole injection in the LED with the QWEBL are predicted by theoretical simulations and confirmed experimentally here. The designed LED structure with the optimized QW thickness of 2 nm not only suppresses the electron overflow of the active region but also enhances the hole injection. The efficiency droop in the LED with the proposed QWEBL structure is

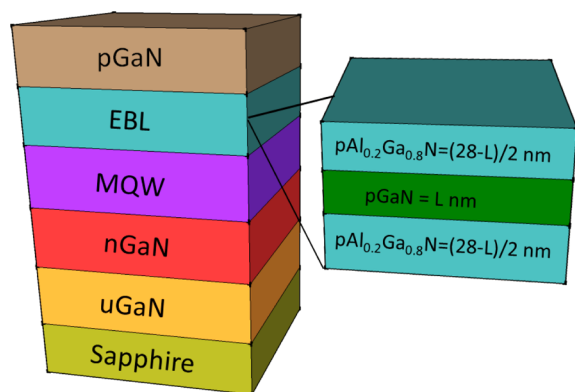
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found to be much smaller than that in the LED with the conventional p-AlGaIn EBL.

## EXPERIMENTAL METHODS

InGaIn/GaN LEDs studied in this work were grown by an Aixtron metal–organic chemical-vapor deposition (MOCVD) system. Two-inch patterned sapphire substrates with periodic cone patterns (with a diameter of 2.4  $\mu\text{m}$ , a height of 1.5  $\mu\text{m}$ , and a pitch of 3  $\mu\text{m}$ ) were used. The growth started with a 30 nm thick low-temperature GaN buffer, followed by an undoped-GaN interlayer ( $\sim 150$  nm thick); detailed information on the interlayer growth can be found in our previous publication.<sup>10</sup> Subsequently, a high-temperature undoped GaN was grown with a thickness of 5  $\mu\text{m}$  followed by a 3  $\mu\text{m}$  Si-doped n-GaN layer. Six pairs of InGaIn/GaN multiple quantum wells (MQWs) were grown with the 3 nm quantum well at 750  $^\circ\text{C}$  and the 12 nm quantum barriers at 800  $^\circ\text{C}$ . The indium composition of the InGaIn well is 15%, and the peak emission wavelength is 450 nm. The p-EBL was grown on the top of the last barrier. The structures were finally covered with a 200 nm thick p-GaN layer. For the reference sample a p-Al<sub>0.2</sub>Ga<sub>0.8</sub>N layer of 28 nm was used as the p-EBL. In the proposed QWEBL LED samples, the p-EBL was a p-(AlGaIn/GaN/AlGaIn) structure with the total thickness kept at 28 nm, and the thin p-GaN layer thickness ( $L$ ) was chosen as being either 2.0 or 4.0 nm. The QWEBL structure is simply realized by closing the TMAI valve during the QW growth of the AlGaIn EBL. The growth temperature and pressure are kept at 980  $^\circ\text{C}$  and 100 mbar the entire time. The thickness and composition of each layer is precisely controlled with mole ratios and growth time based on the calibration runs. The detailed schematic structure is shown in Figure 1. The indium contacts on the epi-



**Figure 1.** Schematic diagrams of the LEDs with the conventional EBL ( $L = 0$ ) and QWEBL ( $L = 2$  and 4 nm).

wafers were made in a circular area of 1.5 mm diameter for characterization purposes. The optical power was measured by an integrating sphere attached to an Ocean Optics spectrometer (QE65000), which was calibrated with a standard light source.

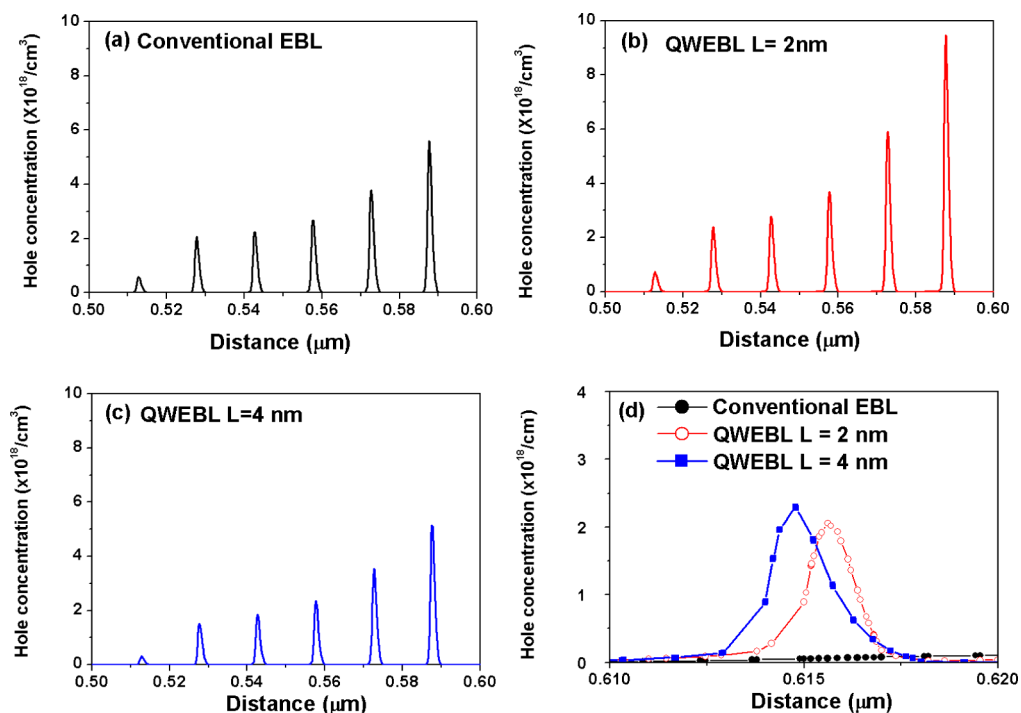
On the basis of our grown structures, numerical simulations were performed using APSYS to understand the working mechanisms of the proposed QWEBL structures. The simulator solves Schrödinger–Poisson equations self-consistently. The simulation has also taken the Coulomb interaction into consideration with the typical dielectric constants of III-nitrides.<sup>11</sup> The simulation parameters including the Auger recombination coefficients, the Shockley–Read–Hall recombi-

nation coefficient, the energy band offset ratio for the MQWs, and the polarization level for devices along the  $c$ -orientation can be found in our previous publication.<sup>12</sup>

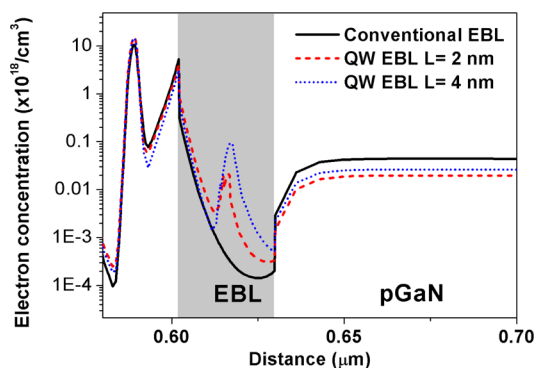
## RESULTS AND DISCUSSION

Figure 2a–c show the simulated results of the hole concentration distribution in the quantum wells for the conventional EBL LED and the QWEBL LEDs at a current density level of 35 A/cm<sup>2</sup>. As depicted in Figure 2a and b, the hole concentration is much higher in each individual quantum well in the QWEBL LED with the p-GaN QW thickness of 2 nm, compared to the conventional EBL LED. However, when the thickness of the p-GaN QW is increased to 4 nm as shown in Figure 2c, the hole concentration in the InGaIn quantum wells becomes lower than that in the conventional EBL LED. Figure 2d highlights the hole concentration in the EBL region. Figure 3 shows the electron concentration in the p-EBL and the p-GaN region. It can be seen that the two QWEBLs enable a lower electron leakage into the p-GaN region, which indicates that the QWEBL allows for a better electron blocking effect than the conventional EBL. Moreover as shown in Figure 3, a higher electron concentration is observed in the p-EBL layer and in the p-GaN region for the QWEBL LED with a 4 nm p-GaN QW than that of the QWEBL LED with a 2 nm p-GaN QW, indicating an even better electron blocking effect of the latter. These results suggest that the electrons can be more effectively confined in the MQW region and that the hole injection efficiency can be improved remarkably by using the QWEBL with  $L = 2$  nm. As a result, the radiative recombination rate in the LED with QWEBL is improved significantly as shown in Figure 4 compared with the conventional EBL LED. However, the radiative recombination rates will drop if the GaN layer thickness is 4 nm. This is due to the stronger hole confinement in the thicker GaN layer, as shown in Figure 2d.

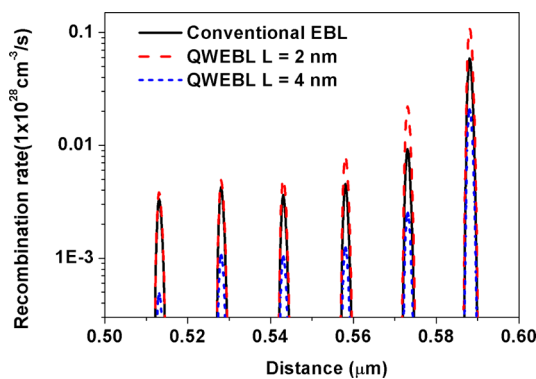
Figure 5a–c present the energy band diagrams of the LEDs with the conventional EBL and the QWEBL at 35 A/cm<sup>2</sup>. As is well known, in conventional EBLs, due to the stronger polarization effect in the QW region, the effective barrier height of the EBL is reduced for electrons and increased for the holes, which lowers the electron blocking capability and hinders the injection efficiency of holes from the p-GaN region into the MQWs.<sup>13</sup> The combination of these effects results in a low hole concentration in the InGaIn MQWs and a large electron leakage, as shown in Figures 2a and 3. However, as the conventional EBL is replaced by the QWEBL, the effective barrier height is changed with the insertion of the p-GaN QW as shown in Figure 5. When the p-GaN QW is 2 nm thick, the effective barrier height for electrons is increased from 366 meV to 416 meV in the QWEBL LED, while its effective barrier height for holes is reduced from 469 meV to 457 meV as shown in Figure 5a and b. These changes in the effective barrier heights for electrons and holes are the main cause of the electron overflow reduction and the hole injection enhancement. The constructive combinational effect of the electron overflow reduction and the hole injection enhancement leads to the enhancement of the radiative recombination rate as shown in Figure 4b. Nonetheless, the change in the effective barrier height is dependent on the thickness of the p-GaN QW. As the p-GaN QW thickness is increased to 4 nm, although the effective barrier height for electrons is increased from 366 meV to 411 meV in the QWEBL LED, the effective barrier height for holes is also increased from 469 meV to 479 meV in the QWEBL LED, as shown in Figure 5a and c. The benefit of the



**Figure 2.** Simulated (a–c) hole concentrations of QWs for the conventional EBL LED and the QWEBL LED at the current injection level of 35 A/cm<sup>2</sup>. (d) Hole concentrations within the EBL region for the conventional EBL LED and the QWEBL LED at the current injection level of 35 A/cm<sup>2</sup>.



**Figure 3.** Electron concentration in EBL and p-GaN for the conventional EBL LED and the QWEBL LED at the current injection level of 35 A/cm<sup>2</sup>.

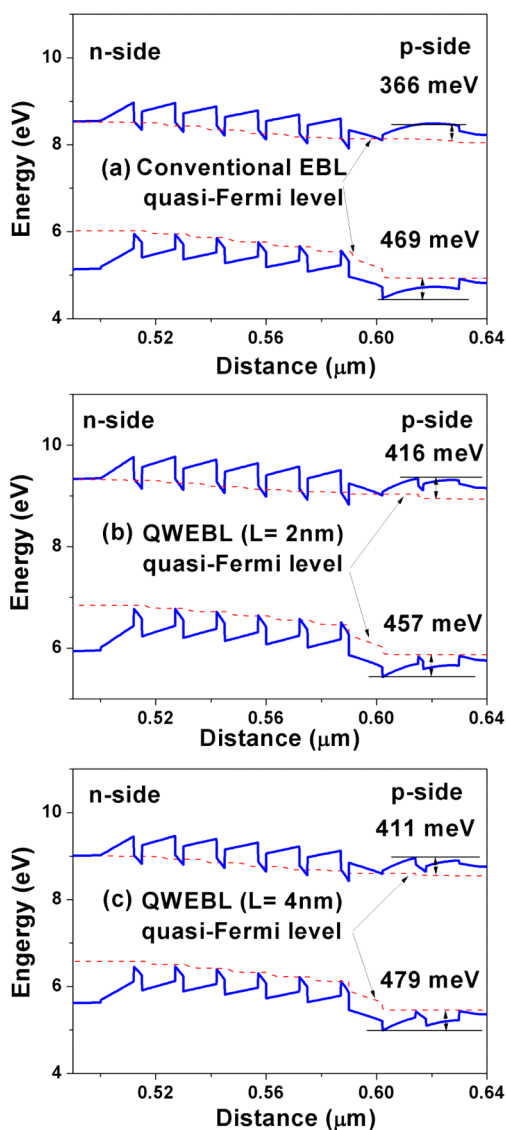


**Figure 4.** Radiative recombination rates at 35 A/cm<sup>2</sup> for the conventional EBL LED and the QWEBL LED.

electron overflow reduction due to the increase of the effective barrier height for electrons is offset by the reduction of hole

injection efficiency due to the increased effective barrier height for holes. This leads to the lower radiative recombination rate as shown in Figure 4c. The reasons for the p-GaN QW thickness dependence of the effective barrier heights of the QWEBL LED are related to the formation of quantized states in the p-GaN QW and carrier tunneling process and will be discussed separately in detail in another publication.

The experimentally measured external quantum efficiency (EQE) and the optical power as a function of the current density are depicted in Figure 6a and b for all the devices. Compared to the conventional EBL LED, the best performance is observed from the QWEBL LED with the p-GaN QW of  $L = 2$  nm. When we evaluate the performance of the QWEBL LED and the conventional EBL LED at the current density of 35 A/cm<sup>2</sup>, the optical output power of the QWEBL LED is 585 mW, which is about 10% higher than that of the conventional EBL LED (530 mW). The efficiency drop of the QWEBL LED at 35 A/cm<sup>2</sup> is only 16%. This is much smaller than that of the conventional EBL LED, which is 31%. The improvement of the optical power and the EQE is well attributed to the improved hole injection and electron blocking in the QWEBL LED, as demonstrated in Figures 2 and 3. However, the optical output power of the QWEBL LED with  $L = 4$  nm is even a little bit lower than the conventional EBL LED at 35 A/cm<sup>2</sup>. This is consistent with the theoretical simulation results shown in Figures 2 and 3. Our results given above are quite different from the prediction of Xia et al., while suggesting that a thicker GaN layer leads to better performance. We believe that the thicker p-GaN QW layer will trap more holes in the EBL region due to the low mobility of holes, as shown in Figure 2d. Meanwhile, the effect of the electron blocking will be reduced due to the thinner effective thickness of the AlGaIn layer, as shown in Figure 3. Therefore, the thinner p-GaN QW in the EBL layer is favorable not only for blocking the electrons but also for easier transportation of holes from the p-type GaN

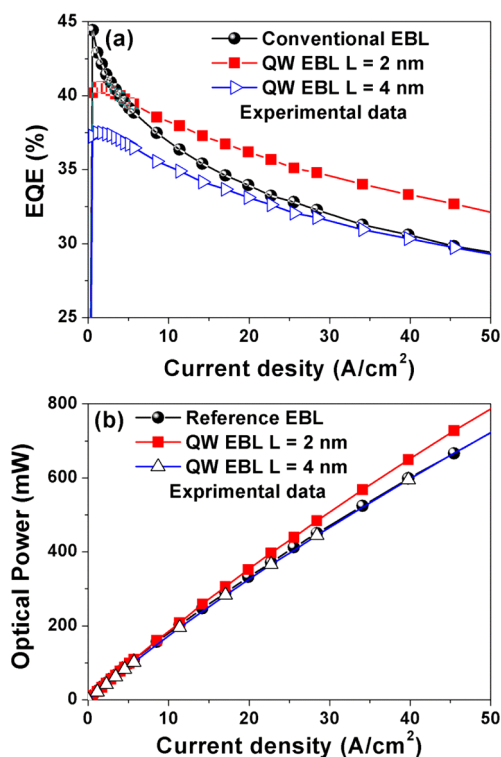


**Figure 5.** (a–c) Energy band diagrams of the LEDs with the conventional EBL and the QWEBL at the current injection level of 35 A/cm<sup>2</sup>.

region to the p-GaN QW of the QWEBL and finally to the MQWs region due to the tunneling effect. It should be noted that the conventional EBL LED shows a better performance at very low current injection level. This could be due to the fact that the initial hole confinement in the QW at low current levels may affect the hole injection efficiency for the QW EBL LED. As the hole tunneling effect increases rapidly with increasing current due to the field-assistance and resonance effects, the hole injection efficiency of the QW EBL LED will surpass that of the conventional EBL LED. The high hole injection efficiency combined with the high electron blocking effect will lead to a better performance at high current levels for the QW EBL LED.

## CONCLUSIONS

In conclusion, blue InGaN/GaN MQW LEDs with the conventional p-AlGaIn EBL and the p-(AlGaIn/GaN/AlGaIn) QWEBL have been investigated both numerically and experimentally. When the QWEBL is adopted, the quantum states are created, which results in the increase of the effective



**Figure 6.** Experimentally measured (a) EQE and (b) optical power output with increasing current density for the conventional EBL and QWEBL LEDs.

barrier height for the electrons and the decrease of that for the holes. Moreover, with the well-controlled thickness of the p-GaN, more holes can tunnel into the MQWs from the p-type GaN region. These effects prevent electron leakage into the p-GaN region and improve the hole injection into the MQW region, which enables the improved optical performance in the LEDs with the proposed QWEBL.

## ASSOCIATED CONTENT

### Supporting Information

The details of the measurement for the optical power, XRD, EL information, and simulation data of hole concentration in the last QW and EBL. This information is available free of charge via the Internet at <http://pubs.acs.org>.

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### Notes

The authors declare no competing financial interest.

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