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SPECIAL TOPIC — Nanophotonics

Improved carrier injection and confinement in InGaN light-emitting diodes containing GaN/AlGaN/GaN triangular barriers*

Li-Wen Cheng(程立文)[1,4,†], Jian Ma(马剑)[1], Chang-Rui Cao(曹常锐)[1], Zuo-Zheng Xu(徐作政)[1], Tian Lan(兰天)[2], Jin-Peng Yang(杨金彭)[1], Hai-Tao Chen(陈海涛)[1], Hong-Yan Yu(于洪岩)[2], Shu-Dong Wu(吴曙东)[1], Shun Yao(尧舜)[3], Xiang-Hua Zeng(曾祥华)[1], and Zai-Quan Xu(徐仔全)[5,‡]

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In this study, an InGaN lighting-emitting diode (LED) containing GaN/AlGaN/GaN triangular barriers is proposed and investigated numerically. The simulation results of output performance, carrier concentration, and radiative recombination rate indicate that the proposed LED has a higher output power and an internal quantum efficiency, and a lower efficiency droop than the LED containing conventional GaN or AlGaN barriers. These improvements mainly arise from the modified energy bands, which is evidenced by analyzing the LED energy band diagram and electrostatic field near the active region. The modified energy bands effectively improve carrier injection and confinement, which significantly reduces electron leakage and increases the rate of radiative recombination in the quantum wells.

Keywords: lighting-emitting diode, gallium nitride, efficiency droop, triangular barrier

PACS: 85.60.Jb, 85.60.Bt, 85.35.Be **DOI:** 10.1088/1674-1056/27/8/088504

1. Introduction

InGaN light-emitting diodes (LEDs) are expected to become important components of next-generation lighting to replace traditional incandescent and fluorescent light bulbs.[1–4] However, the optical performance of InGaN LED is limited by the rapid decrease of emission efficiency with increasing injection current, which is called the "efficiency droop".[5] Several physical models, including Auger recombination,[6] electron leakage,[7,8] and the polarization effect,[9] as well as poor carrier injection[10–13] have been suggested to explain this phenomenon. The specific reason for the efficiency droop is still under debate. However, the carriers including the electrons and hole concentrations in multiple quantum wells (MQWs) can directly affect the LED performance and thus the efficiency droop. Based on this, various methods have been suggested for improving carrier injection and confinement. These include using AlGaN barriers to replace conventional GaN barriers,[14] using AlGaN/GaN/InGaN superlattices as an electron blocking layer (EBL),[15] and using a specially designed AlGaN/GaN superlattice EBL.[16,17]

The LEDs containing AlGaN barriers are more likely to be practically used than the complex superlattice epitaxial structure, because of their relatively simple epitaxial structure. The LEDs with AlGaN barriers can improve the carrier concentration in MQWs. This is because the AlGaN barrier can provide a higher potential barrier to confine carriers in quantum wells (QWs) than conventional GaN barriers. However, the AlGaN barrier can also result in a stronger polarization effect in the active region than conventional LEDs with GaN barriers, because of the greater lattice mismatch between the AlGaN barrier and InGaN well than the conventional GaN barrier and InGaN well. This induces strong band bending and the quantum confined Stark effect (QCSE) in MQWs, which reduces the LED performance.[18,19]

Our aim is to increase carrier confinement without increasing the polarization effect in the active region. For this purpose, we propose an InGaN MQW LED with GaN/AlGaN/GaN triangular (GAGT) barriers. The electrical and optical properties of the proposed LED, as well as those of LEDs with conventional GaN barriers and AlGaN barriers are investigated numerically using APSYS software.[20] The simulations are used to solve the Poisson equation, current continuity equations, carrier transport equation, quantum mechani-

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cal wave equation, and photon rate equation.

2. Structures and parameters

A conventional InGaN MQW LED with GaN barriers (GaN LED) was grown on a *c*-plane sapphire substrate by metal organic chemical vapor deposition. The device structure from bottom to top was a 1.5-μm-thick GaN buffer layer, a 4-μm-thick n-type GaN:Si (3×10^{18} cm^{-3}) layer, the active region including six 2-nm-thick undoped $In_{0.18}Ga_{0.82}N$ QW layers separated by 15-nm-thick undoped GaN barrier layers, a 20-nm-thick p-type $Al_{0.15}Ga_{0.85}N$:Mg (3×10^{18} cm^{-3}) EBL, and a 0.2-μm-thick p-type GaN:Mg (3×10^{18} cm^{-3}) cap layer. The device geometry was square with dimensions of 300 μm ×300 μm. The LED with AlGaN barriers (AlGaN LED) had a similar layered structure except that the GaN barriers were replaced by $Al_{0.05}Ga_{0.95}N$. Similarly, the LED with GAGT barriers (GAGT LED) had the GaN barriers replaced by GAGT barriers. For the GAGT barriers, the aluminum (Al) composition of the AlGaN barrier was gradually increased from 0 to 0.1, and then decreased to 0. Schematic band diagrams of the three LEDs are shown in Fig. 1. The total Al content of the AlGaN LED was the same as that of GAGT LED. The parameters used in the simulation were consistent with those used in our previous work.[21,22]

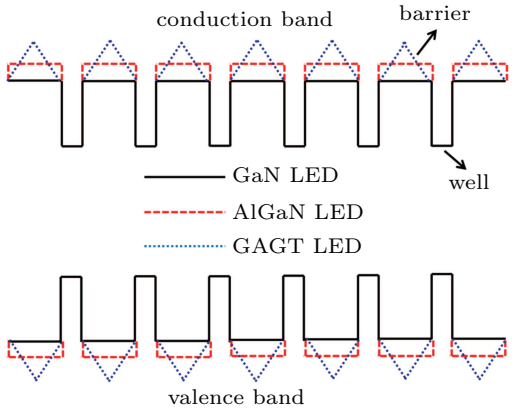


Fig. 1. (color online) Schematic diagrams of the MQW band structures of GaN LED (solid line), AlGaN LED (red dashed line), and GAGT LED (blue dotted line).

3. Results and discussion

The simulated output power characteristic and internal quantum efficiency (IQE) of the three devices as a function of injection current are a common standard of output performance. As shown in Fig. 2, the GAGT LED exhibits the best performance in the three structures in the entire current injection range, and especially at high current injection. The output power of the AlGaN LED is 84.46% higher than that of the conventional GaN LED as shown in Fig. 2. This corresponds to an IQE improvement of approximately 81.04%. The efficiency droop is defined as $(IQE_{max}–IQE_{150\ mA})/IQE_{max}$. The calculated efficiency droop is 47.39% for the AlGaN LED and 62.12% for the conventional GaN LED. For the GAGT LED, the output power is 199.22 mW, which is 217.94% higher than that for the GaN LED. The efficiency droop for the GAGT LED is 13.36% lower than that for the GaN LED as shown in Figs. 2(a) and 2(b). Thus, the output performance is markedly improved when conventional GaN barriers are replaced by GAGT barriers. The IQE curves indicate that the performance of the GAGT LED is superior to those of the conventional GaN LED and AlGaN LED throughout the entire current injection range, and especially at high injection current.

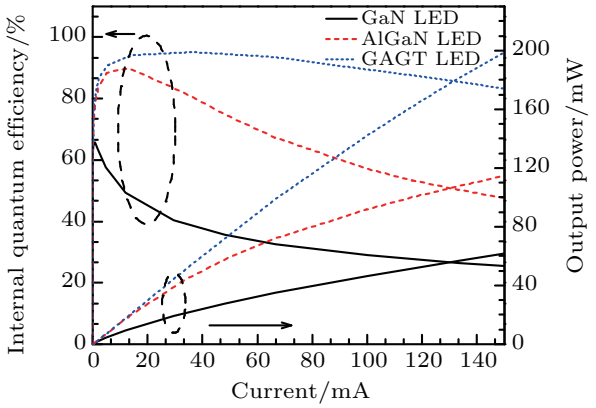


Fig. 2. (color online) Curves of light output power and internal quantum efficiency versus current for three different LEDs.

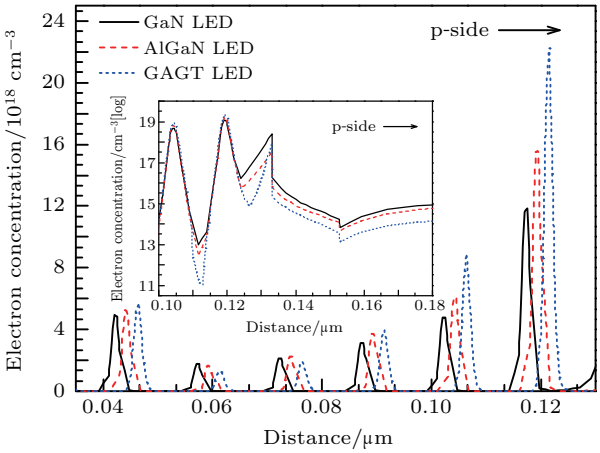


Fig. 3. (color online) Distribution of electron concentrations near the active region of the three LEDs at 150 mA. The inset shows curves of logarithm of electron concentrations versus distance for three different LEDs.

The calculated electron distributions near the active region for the three LED structures at 150 mA are shown in Fig. 3. For the GAGT LED, the electron concentration in the QWs is substantially increased compared with for the AlGaN LED, especially in the last QW. The electron concentration in the QWs for the AlGaN LED is much higher than that for the conventional GaN LED. This indicates that electron confinement in the GAGT LED QWs is significantly improved. The inset in Fig. 3 shows the curves of the logarithm of electron concentrations varying with distance for the three LEDs, indicating that the electron concentration on the p-side of the AlGaN LED is lower than that of the conventional GaN LED. The electron concentration on the p-side of the GAGT LED is

lower still. The concentration of electrons on the p-side is almost one order of magnitude lower than those in the GaN LED and AlGaN LED. This indicates that the GAGT LED has the lowest electron leakage to the p-side. This is further evidence that the GAGT LED has the best electron confinement in the three LEDs.

Figure 4 shows the hole distribution near the active region for the three LEDs at 150 mA. Holes each have a relatively large effective mass and low mobility compared with electrons. Thus, most holes accumulate near the p-side, and hole concentration in the QWs gradually decreases from the p-side to n-side. Figure 4 shows that the hole concentration in the QWs in the AlGaN LED is higher than that in the conventional GaN LED. However, the hole concentration in the QWs, especially in the last QW, is much higher in the GAGT LED. This indicates that the GAGT LED possesses the best hole confinement in the three tested LEDs. The inset in Fig. 4 shows the magnified part of the logarithm curve of the hole concentration for each of the three LEDs near the p-side. Many holes accumulate at the last barrier-EBL interface in the GAGT LED. This benefits the injection of holes into the QWs from the p-side. The reasons for this hole accumulation are analyzed in terms of energy band diagrams (discussed later).

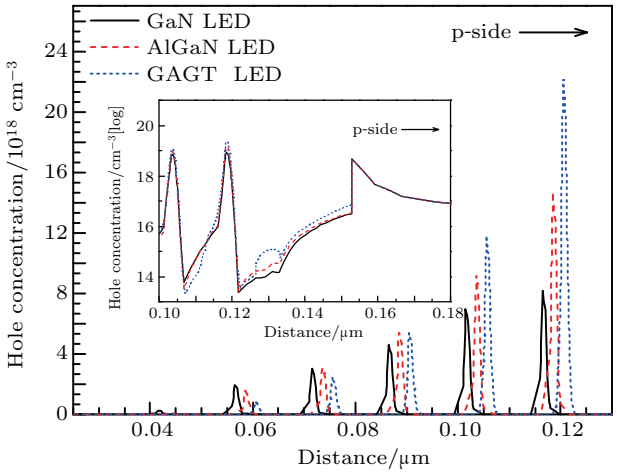


Fig. 4. (color online) Distributions of hole concentrations near the active region of the three LEDs at 150 mA. The inset shows the magnified part of the logarithm curve of the hole concentration versus distance for each of three LEDs near the p-side.

Figure 5 shows electron current density profiles near the active region, for the three LEDs at 150 mA. Electrons are injected from the n-side and then recombine with holes in the QWs. This reduces the electron current density along the growth direction. The electron leakage current is defined as the electron current leaking out of QWs into the p-side. The improved carrier confinement and hole injection leads to a much lower electron leakage current density on the p-side of the GAGT LED. The electron leakage current densities are about 164.4 A/cm^2, 113.5 A/cm^2, and 33.6 A/cm^2 in the conventional GaN LED, AlGaN LED, and GAGT LED, respectively. This indicates that the electron leakage current is significantly suppressed in the GAGT LED.

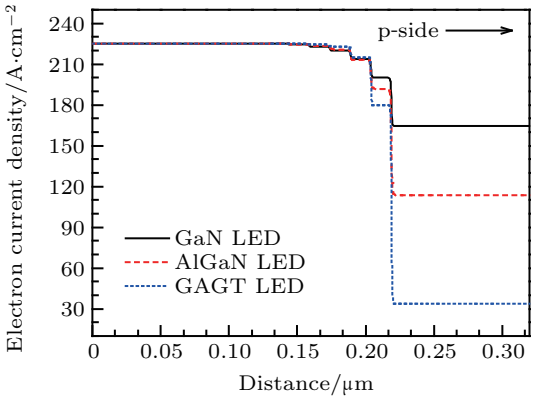


Fig. 5. (color online) Electron current density profiles near the active region for three different LEDs at 150 mA.

Energy band diagrams near the active region of the three LEDs at 150 mA are shown in Fig. 6. Significant band bending arises due to the strong electrostatic field in the LED (discussed later). For the GaN LED, a potential barrier for electrons forms at the interface of the last barrier/EBL. This barrier arises due to the band offset between the last barrier and EBL in the conduction band, which is used for blocking electron transport from the active region to the p-side. Another potential barrier for holes forms because of the band offset between the last barrier and EBL in the valence band, which suppresses hole injection from the p-side to the active region. Confining more electrons in the QWs and injecting more holes into the QWs require the potential barrier for electrons to be as high as possible, and that for holes to be as low as possible. The downward band bending in the last barrier reduces the effective barrier height for electrons, and increases that for holes (Fig. 6(a)). In the AlGaN LED, the lattice of the last AlGaN barrier well matches that of the AlGaN EBL, compared with the conventional GaN barrier in the GaN LED. This means that downward band bending in the last barrier is alleviated. The effective barrier height for electrons increases from 282 meV to 285 meV, while that for holes decreases from 319 meV to 299 meV. This situation is further improved in the GAGT LED. The GAGT LED has the highest effective barrier height for electrons of 290 meV, and the lowest effective barrier height for holes of 275 meV. This results in the highest carrier concentration including electrons and holes in the QWs, and the lowest electron leakage current density on the p-side (as discussed above). A shallow potential well for holes exists in the valence band. Many holes therefore accumulate, which promotes hole injection from the p-side to the active region. Figure 6(d) shows that the QW for the AlGaN LED is deeper than that for the conventional GaN barrier. The GAGT LED has an angular barrier forming the deepest QW in the three tested LEDs. This indicates that the GAGT LED has the best carrier confinement.

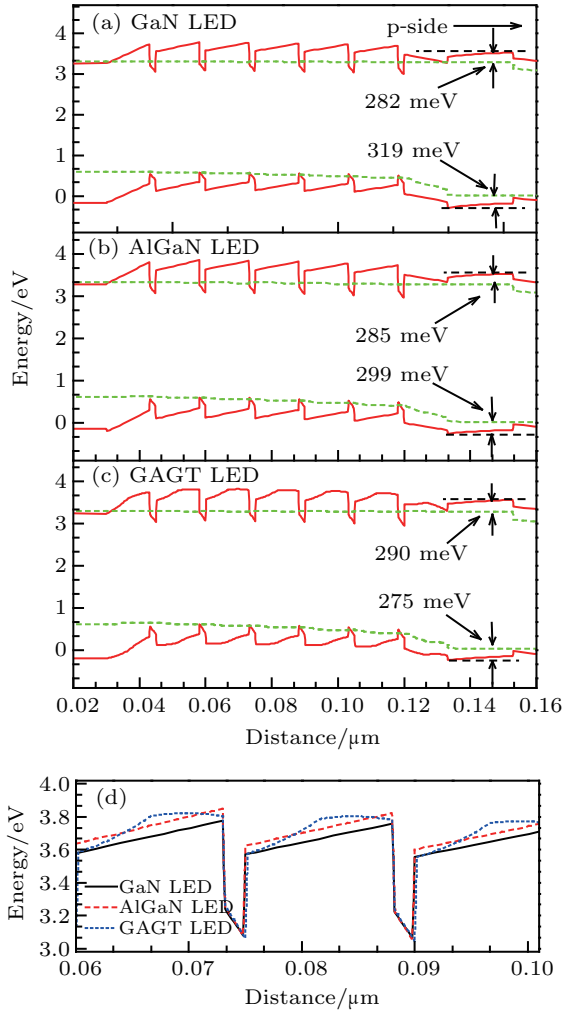


Fig. 6. (color online) Energy band diagrams of (a) conventional GaN LED, (b) AlGaN LED, (c) GAGT LED at 150 mA, and (d) magnified part of conduction band of the middle two QWs for each of three LEDs.

Figure 7 shows the electrostatic fields near the active region and EBL, for the three LEDs at 150 mA. Strong electrostatic fields exist in the LEDs, due to the polarization effect in the GaN-based material. These electrostatic fields cause the QCSE and poor overlap of the electron and hole wave functions in the QWs, which reduces the recombination efficiency. The electrostatic fields in the QWs of the GAGT LED are similar to those in the AlGaN LED, and are stronger than those in the conventional GaN LED. The main cause for this is the similar Al content of the barriers in the GAGT LED and AlGaN LED, and the absence of Al in the barriers of the GaN LED. The magnified diagram shows that the electrostatic field in the last QW in the GAGT LED exhibits a different tendency. The electrostatic field is almost the same as in the conventional GaN LED, and is lower than that in the AlGaN LED. This may be due to the large screening effect, because many carriers accumulate in this last QW. The electrostatic field in the last barrier in the GAGT LED is also the lowest, which reduces band bending in the last barrier, increases the effective potential height for electrons, and reduces the height for holes (as discussed earlier). The electrostatic field is the highest in the other barriers, and the profile is triangular, which gives rise to the deepest wells to confine carriers in the electrostatic fields of the three tested LEDs.

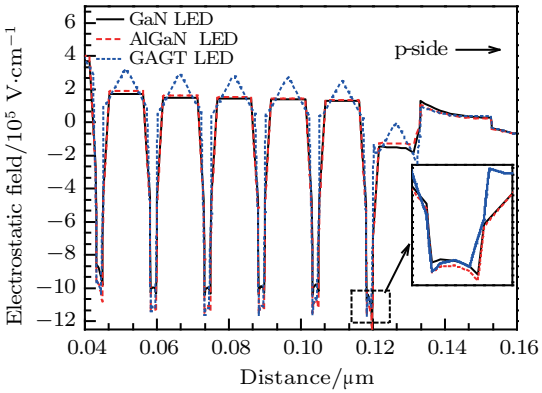


Fig. 7. (color online) Electrostatic fields near the active region of the three LEDs at 150 mA, with inset showing a magnified diagram of electrostatic field in the last QW.

The radiative recombination rate for each of the three LEDs is shown in Fig. 8. The radiative recombination rate mainly arises from the last QW, because it has the highest electron and hole concentrations in the six QWs. The GAGT LED has the highest radiative recombination rate in the three tested LEDs. This is because the electron and hole concentration in the last QW are highest, and also because of the relatively high recombination efficiency due to the low electrostatic field in the last QW. The GAGT LED therefore exhibits the best optical performance in the three tested LEDs.

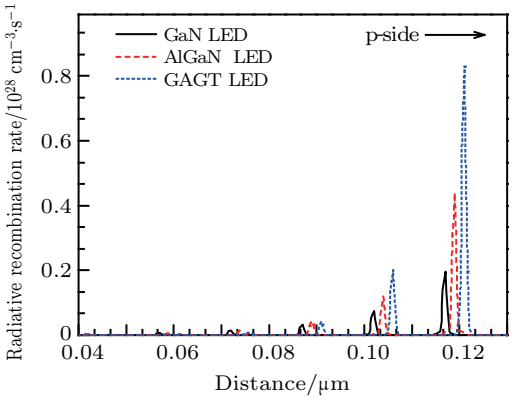


Fig. 8. (color online) Radiative recombination rates versus distance of three different LEDs at 150 mA.

4. Conclusions

An InGaN LED with GAGT barriers has been proposed and investigated numerically. When the conventional GaN barriers are replaced by GAGT barriers, the output power increases from 62.66 mW to 199.22 mW, and the efficiency droop decreases from 62.12% to 13.36%. The simulation results indicate that the carrier injection and confinement in the GAGT LED are significantly improved. This leads to reduced electron current leakage and increased radiative recombination. The major physical origins of these improvements are

thought to be the increased effective barrier height for electrons and reduced effective barrier height for holes, as well as the formation of a shallow potential well for holes in the valence band. These factors result in more holes injected into the QWs from the p-type region.

References

[1] Krames M R, Shchekin O B, Mueller-Mach R, Mueller G O, Zhou L, Harbers G and Craford M G 2007 *J. Disp. Technol.* **3** 160

[2] Dhanabalan S C, Ponraj J S, Guo Z, Li S, Bao Q and Zhang H 2017 *Adv. Sci.* **4** 1600305

[3] Ponraj J S, Xu Z Q , Dhanabalan S C, Mu H, Wang Y, Yuan J, Li P, Thakur S, Ashrafi M, Mccoubrey K, Zhang Y, Li S, Zhang H and Bao Q 2016 *Nanotechnology* **27** 462001

[4] Dhanabalan S C, Ponraj J S, Zhang H and Bao Q 2016 *Nanoscale* **8** 6410

[5] Piprek J 2010 *Phys. Status Solidi A* **207** 2217

[6] Ivel, J, Martinelli L, Peretti J, Speck J S and Weisbuch C 2013 *Phys. Rev. Lett.* **110** 177406

[7] Xu J, Schubert M F, Noemaun A N, Zhu D, Kim J K, Schubert E F, Park Y, *et al.* 2009 *Appl. Phys. Lett.* **94** 011113

[8] Zhao H, Liu G, Zhang J, Arif R A and Tansu N 2013 *J. Disp. Technol.* **9** 212

[9] Kuo Y K, Horng S H, Tsai, M C, Yen S H and Chang S H 2010 *Opt. Commun.* **283** 3698

[10] Kim M H, Schubert M F, Dai Q, Kim J K, Schubert E F, Piprek J and Park Y 2007 *Appl. Phys. Lett.* **91** 183507

[11] Xie J, Ni X, Fan Q, Shimada R, Özgür Ü and Morkoç H 2008 *Appl. Phys. Lett.* **93** 121107

[12] Ni X, Fan Q, Shimada R, Özgür Ü and Morkoç H 2008 *Appl. Phys. Lett.* **93** 171113

[13] Wang C H, Chang S P, Chang W T, Li J C, Lu Y S, Li Z Y and Wang S C 2010 *Appl. Phys. Lett.* **97** 181101

[14] Chang J Y, Tsai M C and Kuo Y K 2010 *Opt. Lett.* **35** 1368

[15] Kim K S, Kim J H, Jung S J, Park Y J and Cho S N 2010 *Appl. Phys. Lett.* **96** 091104

[16] Zhang Y Y and Yin A Y 2011 *Appl. Phys. Lett.* **99** 221103

[17] Gong C C, Fan G H, Zhang Y Y, Xu Y Q, Liu X P, Zheng S W, Yao G R and Zhou D T 2012 *Chin. Phys. B* **21** 068505

[18] Gorai A, Panda S and Biswas D 2017 *Optik* **140** 665

[19] Kuo Y K, Chang J Y, Tsai M C and Yen S H 2009 *Appl. Phys. Lett.* **95** 011116

[20] APSYS by Crosslight Software Inc Burnaby Canada (http://www.crosslight.com)

[21] Cheng L, Wu S, Xia C and Chen H 2015 *J. Appl. Phys.* **118** 103103

[22] Cheng L and Wu S 2014 *IEEE J. Quantum Electron.* **50** 261