Droop improvement in blue InGaN light-emitting diodes with GaN/InGaN superlattice barriers*

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GaN/InGaN superlattice barriers are used in InGaN-based light-emitting diodes (LEDs). The electrostatic field in the quantum wells, electron hole wavefunction overlap, carrier concentration, spontaneous emission spectrum, light-current performance curve, and internal quantum efficiency are numerically investigated using the APSYS simulation software. It is found that the structure with GaN/InGaN superlattice barriers shows improved light output power, and lower current leakage and efficiency droop. According to our numerical simulation and analysis, these improvements in the electrical and optical characteristics are mainly attributed to the alleviation of the electrostatic field in the active region.

Keywords: GaN-based light-emitting diodes, GaN/InGaN superlattice barriers, electrostatic field

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1. Introduction

InGaN/GaN-based high-brightness light-emitting diodes (LEDs) have attracted much attention because of their applications in signage, back lighting, and general illumination. A major obstacle for InGaN-based light-emitting diodes (LEDs) to further penetrate into the general illumination market is that their efficiency suffers a substantial decrease as the injection current increases; this well-known phenomenon is called the "efficiency droop". The efficiency of conventional GaInN/GaN multi-quantum-well (MQW) LEDs generally reaches its peak value at forward current densities less than 10 A/cm^2, and monotonically drops as the current increases further.[1] The efficiency droop is caused by a nonradiative carrier loss mechanism that becomes dominant as the injection current increases.[2] Electron leakage,[1–4] lack of hole injection,[5–8] carrier delocalization,[9,10] Auger recombination,[11,12] defects,[13] and junction heating[14] are suggested as explanations. Nevertheless, the physical origin of "efficiency droop" remains debatable and, hence, an overall solution is still lacking.

For the exploration of efficiency droop in blue InGaN LEDs, the polarization effect that arises from the lattice mismatch between quantum barriers and quantum wells is a critical factor that causes poor lighting characteristics.[15,16] The large polarization field within the active region results in the quantum-confined Stark effect and poor overlap between the electron and hole wave functions, and consequently reduces the radiative recombination rate and internal quantum efficiency of the optoelectronic device. Many scientists have tried to use InGaN barriers to replace conventional GaN barriers, and the polarization effect between the well and barrier could be effectively reduced.[17,18] However, under this circumstance, the potential carrier confinement height may be reduced due to the relatively small energy band gap of InGaN. In this article, we propose a design with a GaN/InGaN superlattice to enhance the emission efficiency of InGaN/GaN MQW LEDs at high injection currents. The electrical and optical properties of the conventional and GaN/InGaN superlattice barrier LEDs are investigated numerically with the APSYS simulation program, which was developed by Crosslight Software Inc.[19]

2. Structure and parameters

The conventional blue InGaN/GaN MQW LED used as a reference is grown on a (0001) C-face sapphire substrate. The device structure consists of a 1.5-μm-thick GaN buffer layer, a 4-μm-thick n-type GaN:Si (5×10^{18} cm^{-3}), six periods of $In_{0.16}Ga_{0.84}N$(3 nm)/GaN(10 nm) MQW active regions, followed by a 20-nm-thick p-type $Al_{0.1}Ga_{0.85}N$:Mg (1×10^{18} cm^{-3}) electron blocking layer (EBL), and a 0.17-μm-thick p-type GaN:Mg (1×10^{18} cm^{-3}) cap layer. The device geometry is 300 μm×300 μm. The internal absorption within the LED device is set to be 500 m^{-1}, and the light extraction efficiency is assumed to be 0.78. The built-in interface charges due to spontaneous and piezoelectric polarization are calculated by the methods developed by Fiorentini *et al.*[20] Theoretically, about 40% of the calculated interface charges are used to compensate for the fixed defects and other interface charges.

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The hole mobility values are assumed to be 2 $cm^2/V{\cdot}s$ for InGaN and 10 $cm^2/V{\cdot}s$ for AlGaN in the simulation.[21] The other material parameters used in the simulation can be found in Ref. [22]. The bulk radiative recombination outside the QW regions is excluded from the internal quantum efficiency (IQE) calculations.

The bandgap energies of InGaN and AlGaN ternary alloys can be expressed, respectively, as[23]

$$E_g(In_xGa_{1-x}N) = x\cdot E_g(InN) + (1-x)\cdot E_g(GaN) - 1.4x\cdot(1-x), \quad (1)$$

$$E_g(Al_xGa_{1-x}N) = x\cdot E_g(AlN) + (1-x)\cdot E_g(GaN) - 0.7x\cdot(1-x), \quad (2)$$

where E_g(InN), E_g(AlN), and E_g(GaN) are the bandgap energies of InN, AlN, and GaN, with values of 0.78, 6.25, and 3.51 eV, respectively.[22] For the simulation of LEDs with GaN/InGaN superlattice barriers, the device structure and parameters are all the same as those of the conventional LED, except that the barriers are divided into five parts: the first, third, and fifth parts are all 2-nm $In_{0.05}Ga_{0.95}N$, and the second and fourth part are both 2-nm GaN. Note that it is the $In_{0.05}Ga_{0.95}N$ layer that contacts QWs at the well and barrier interface. With this design, in addition to higher mobility for both electrons and holes, it might be possible that the LED could reduce the polarization charges at the interface between the well and barrier at the expense of losing potential carrier confinement height. The schematic diagrams of the two LED structures under study are depicted in Fig. 1.

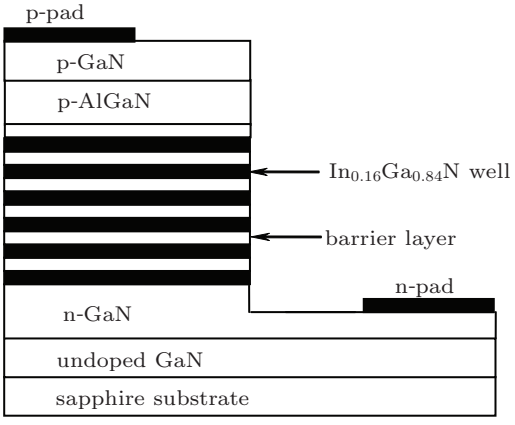


Fig. 1. The structures of the two LEDs under study.

The barriers and their structure parameters are given in Table 1.

Table 1. The barriers and their structure parameters.

Structures	Composition	Thickness/nm
GaN (conventional)	GaN	10
GaN/InGaN	$In_{0.05}Ga_{0.95}N$/GaN/	2/2/2/2/2
Superlattices	$In_{0.05}Ga_{0.95}N$/GaN/	(total thickness = 10)
	$In_{0.05}Ga_{0.95}N$	

3. Results and discussion

Figures 2(a) and 2(b) show the overlap between the electron hole wave functions of these two LEDs in the quantum wells. Due to the smaller lattice mismatch between $In_{0.16}Ga_{0.84}N$ and $In_{0.05}Ga_{0.95}N$ than between $In_{0.16}Ga_{0.84}N$ and GaN, the polarization effect in the quantum wells of the GaN/InGaN superlattice barrier LED is much smaller than that in the conventional one. We calculate the electrostatic fields in the quantum wells of the two LEDs according to the equations developed by Bernardini.[23] The polarization field is about 1.2 MV/cm for the conventional LED, and 0.9 MV/cm for the GaN/InGaN superlattice barrier LED, as shown in Fig. 2(c). The reduced polarization field is beneficial to increasing the overlap between the electron and hole wave functions. The percentage of overlap between the electron and hole wave functions is 25.7% for the GaN/InGaN superlattice barrier structure, and 21.3%

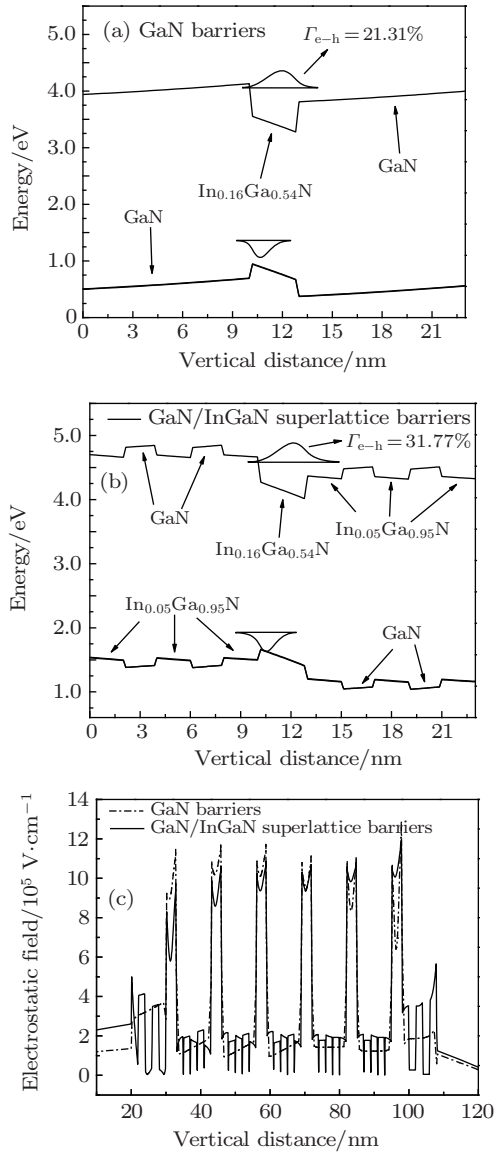


Fig. 2. The electron hole wave function overlaps for the cases of (a) the conventional LED, (b) the GaN/InGaN superlattice barrier LED, and (c) the electrostatic fields throughout the two LED structures.

for the conventional structure. The increased overlap between the electron and hole wave functions results in more electrons contributing to radiative recombination. Therefore, the issue of electron leakage is accordingly diminished.

The simulated carrier concentrations of the two samples in the MQWs, cut from n-side to p-side at 50 mA, are plotted in Fig. 3. It can be seen that the difference between the two structures is obvious. The electron and hole concentrations in a conventional LED QW are mostly distributed in the last quantum well near the p-side, but for the GaN/InGaN superlattice barrier LED, the electron concentration sharply decreases from the n-side to the p-side. In contrast to the carrier distribution, more electrons and holes exist in the active region of the GaN/InGaN superlattice barrier LED than those of the conventional LED. The total electron concentration increases about 18.75% and the hole concentration about 67.1% when the conventional GaN barriers are replaced by GaN/InGaN superlattice barriers.

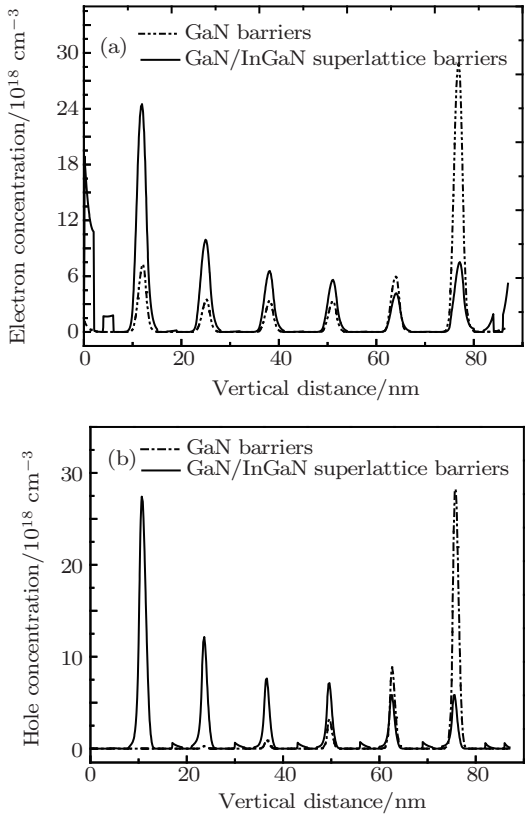


Fig. 3. The (a) electron concentration and (b) hole concentration of the two LEDs under study.

Figure 4 shows the energy band diagrams and quasi-Fermi levels of the LEDs with GaN barriers and GaN/InGaN superlattice barriers at 20 mA. It can be observed that in Fig. 4(b), the barrier potential height in the conduction band of the GaN/InGaN superlattice barriers does not reduce compared with that in the conventional structure. In the conduction band, there are six low-energy points where the energies are all below the quasi-Fermi level. According to the equation:

$$n = N_{\mathrm{C}} \exp\left(\frac{E_{\mathrm{Fn}} - E_{\mathrm{C}}}{KT}\right),$$

most of the electrons accumulate at these six points. The electron concentrations can be higher than 10^{19} cm^{-3}, as indicated in Fig. 3.

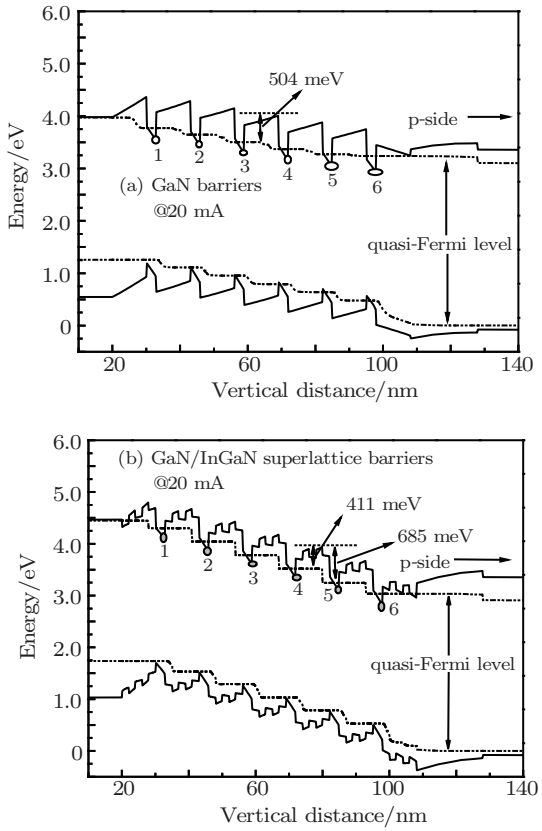


Fig. 4. Energy band diagrams of the two LEDs under study at 20 mA.

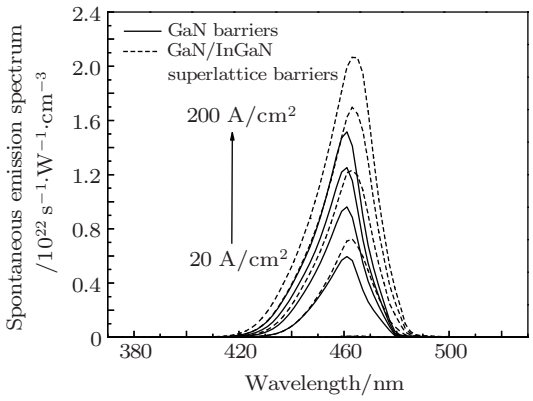


Fig. 5. The calculated spontaneous emission spectra of the two structures.

The spontaneous emission spectra of the two structures are shown in Fig. 5. The spontaneous emission rates of the two structures both increase as the forward current increases from 20 mA to 200 mA. The peak wavelengths of the GaN barrier LED and GaN/InGaN superlattice barrier LED are 460 nm

and 465 nm at 200 mA, respectively. And there is no emission from the GaN/InGaN superlattice barriers. The spontaneous emission rates in the GaN/InGaN superlattice barrier LEDs are larger than those in the GaN barrier LEDs at each forward current.

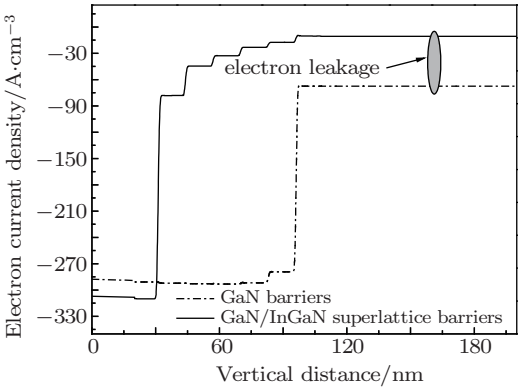


Fig. 6. The electron currents through the two LED structures under study.

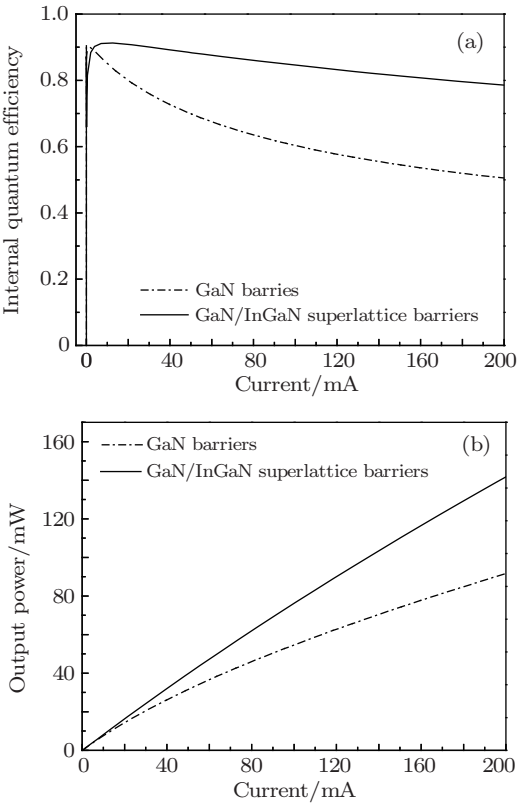


Fig. 7. (a) IQE and (b) light output power, each as a function of current, for the two LED structures under study.

Due to the increased hole concentration in the quantum wells, more electrons can be recombined with holes in the active region. Thus, the electron leakage can be reduced. As shown in Fig. 6, the electron current of the GaN/InGaN superlattice barrier LED in the p-type region is greatly reduced compared with that of the conventional one. The electron leakage in the GaN/InGaN superlattice barrier LED can almost be neglected. The escaped electrons from the MQW active region can recombine with holes in the p-type region, thereby lowering the LED efficiency. This reveals that the electron leakage current due to the polarization fields is one of the dominant mechanisms that results in efficiency droop. For the GaN/InGaN superlattice barrier LED, it can reduce the polarization effect between the barrier and wells, and furthermore reduce the electron leakage out of the active region.

Because of the advantages in the alleviation of the electrostatic field in the quantum wells and the reduction of electron leakage to the p-side, the performance of the GaN/InGaN superlattice barrier LED is expected to be superior to that of the conventional LED. Figure 7 shows the IQE and light output power, each as a function of current, for the two LED structures under study, indicating that the GaN/InGaN superlattice barrier LED has better lighting efficiency and light output power, especially at high currents.

4. Conclusions

In this paper, InGaN-based LEDs with traditional GaN barriers and GaN/InGaN superlattice barriers are numerically investigated using the APSYS simulation software. It is found that the conventional structure with GaN barriers has severe electron leakage, and shows inferior light output power with large efficiency droop. In contrast, the LED with GaN/InGaN superlattice barriers shows improved light output power, with lower current leakage and efficiency droop. Based on numerical simulation and analysis, these improvements on the electrical and optical characteristics are mainly attributed to the alleviation of the electrostatic field in the active region.

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