

# Research on the Electron-blocking Layers in the GaN-based LEDs

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**Abstract.** The electron overflow happening in the active region of GaN-based light-emitting diodes (LEDs) will decrease the rate of radiative recombination, leading to a reduction of light output power. To deal with the problem, the electron blocking layer (EBL) is designed to weaken electrons leakage. Various designs and structures of the electron blocking layers embedded in the multiple quantum layers of GaN-based LEDs are reviewed in this paper. Designs such as trapezoidal EBL, step-graded superlattice EBL, and hybrid EBL can all effectively limit the amount of electron overflow. With many designs of EBL, LEDs are expected to have a wider range of applications in the opto-electric field.

**Keywords:** Electron-blocking layers, electron overflow, GaN-based LEDs, Multiple-quantum-wells.

## 1. Introduction

In the past few decades, GaN-based materials were developed and advanced tremendously. This progress made it to become a promising material in the optoelectronic field. To be specific, it is especially useful for light-emitting diodes (LEDs) due to its wide direct bandgap. GaN-based LED has a wide range of applications in society, including color displays, illuminations, and beyond illuminations.

In the multiple quantum wells (MQWs) of the GaN-based LEDs, electrons and holes recombined, and then photons are formed. The particular region for carrier recombination is called the active region. However, due to the effect of the electric static field, partial amounts of electrons are endowed with too much kinetic energy, so they would run out of the region of MQWs. Due to the running out of electrons, the recombination efficiency for electrons and holes will be negatively influenced, leading to a light output power decreasing. This particular phenomenon can be understood as electron overflow or electrons leakage. To deal with such a problem, electron-blocking layers (EBLs) were designed to lower the amount of electron leakage out of the active region.

This paper made a summary of the progress and innovations of electron-blocking layers in GaN-based LEDs. By using various unique structures of electron blocking layers, 1) electron confinements can be improved; 2) hole injection efficiency can be enhanced; 3) the light output efficiency can be increased.

## 2. Designs Of Electron-Blocking Layers

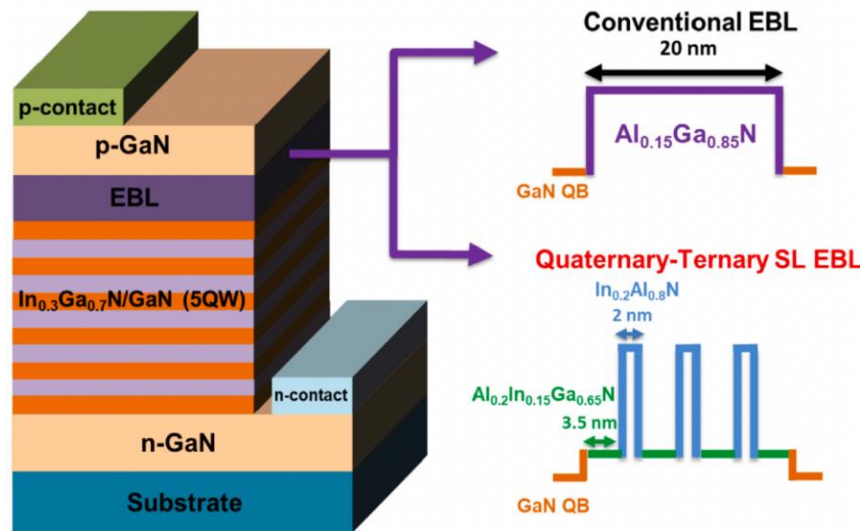
### 2.1. Electron-blocking Layers with superlattice

The authors investigated the electric and optic characteristics of AlGaIn-based DUV-LED with AlnGaIn/AlnN SL EBL. Research results showed that DUV-LEDs with AlnGaIn/AlnN SL EBL had better ability of electron confinement as compared to conventional LEDs. In addition, the radiative recombination and the IQE of the proposed LED were respectively increased by 219% and 49%, and the structure showed almost no efficiency droop [1].

The team of authors investigated the last layer of AlGaIn/InGaIn SLs and the effect of p-AlGaIn/InGaIn SLs EBL to the performance of LEDs. In the three samples of LEDs, the one with p-AlGaIn/InGaIn SLs EBL and u-AlGaIn/InGaIn SLs LQB showed highest output power. At 200mA, the output power of LED C was increased by 27.5%, and its efficiency droop got confined, which was 28.5% and was lower than 34% of LED A. Through analyzing the distribution of holes and

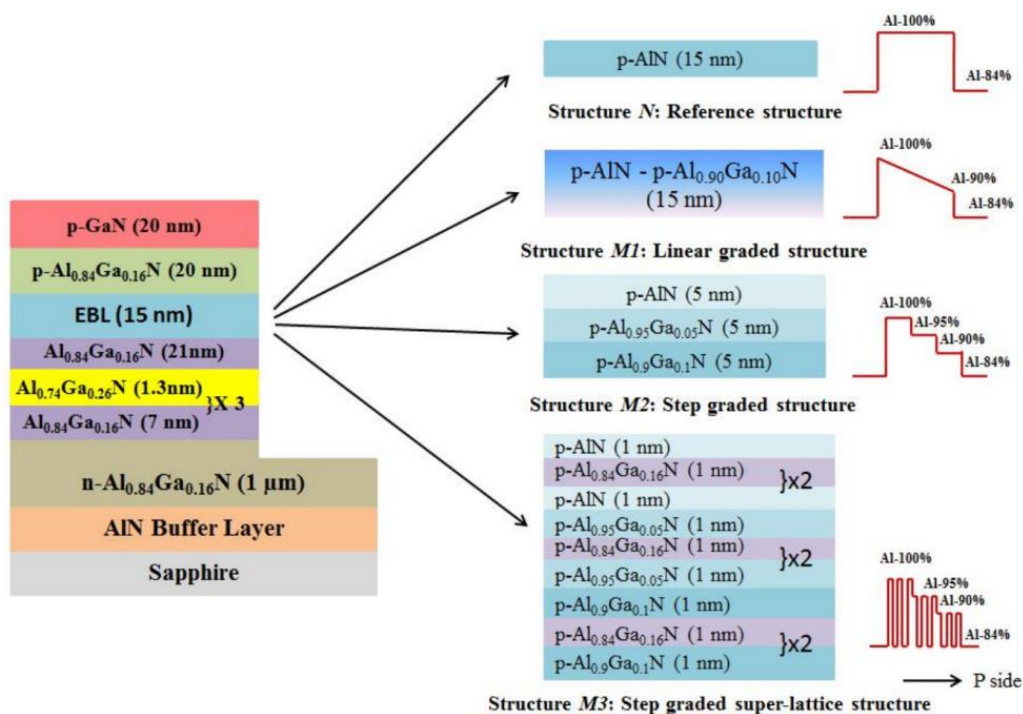
electrons in the MQWs, researchers found their change in distribution were due to the change of potential barrier[2].

For solving unnecessary electron blocking problems, the authors' team adopted SL EBLs with quaternary-ternary, which is shown in Figure 1, to take the place of conventional EBLs. The team decreased the effect height of holes' potential barrier about -87meV so that the structure could effectively increase the hole injection rate for 50%. The structure also relatively improved the recombination rate for 79%. Finally at the current of 100A/cm<sup>2</sup>, the overall efficiency droop decreased 23% [3].



**Figure 1.** This is the schematic diagram from the research team studying green InGaN-based MQW structure [3]

As shown in Figure 2, by adding step-graded SL structures into DUV LED, the research team found that IQE could be effectively improved. To be specific, the team found step-graded SL structure could improve the efficiency of injecting holes into MQWs, and it could also solve electron leakage. Moreover, at the current density of 170A/cm<sup>2</sup>, IQE of such structure is 15% higher than conventional EBL LEDs, and the efficiency droop is 15% lower[4].

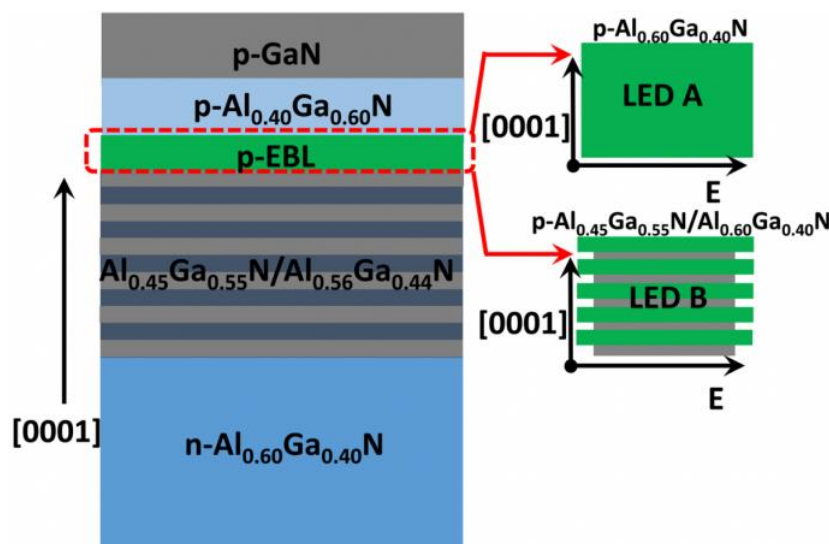


**Figure 2.** The schematic of the step-graded super-lattice EBL structure [4]

The author team found, compared to other LEDs, LEDs adopted InGaN/AlInGaN SL EBL showed lower current-voltage curve, electron leakage, and higher light output. Efficiency droop can also be relieved. The team conducted numerical investigation by using APSYS simulation software. The team concluded when using InGaN/AlInGaN SL EBL, higher hole injection and better electron confinement can be got [5].

To alleviate the implement of NUV-LEDs hole injection due to p-type AlGaN EBL and the problem of electron leakage made by banding downward at the conduction band, the research team adopted P-AlInGaN/AlGaN SPSL-EBL. The proposed structure could increase the potential barrier and decrease holes. In addition, the outer band could be banded upward so that the hole injection was facilitated. At 200mA, the forward voltage was decreased from 3.88 to 3.74V, and, most importantly, the team increased the light output power to 101.6%. The team looked forward on applications in the UV curing field [6].

In Figure 3, the research team proved from experiments and simulations that blue-green LEDs with p-type EBL had great potential in optoelectronic devices. Through simulation, the team found that p-AlGaN EBL inside the N-polar LED could better block the overflow of electrons, and it was easier for hole to be injected into MQWs. Thus, the turn-on voltage of N-polar LEDs would be lower. Through experiment, when adding forward bias to two pairs of MQWs, the MQW of blue-green LEDs had main wavelength around 480nm [7].



**Figure 3.** Schematic structure of the SL p-type EBL for Mg Doping efficiency[7]

## 2.2. P-type Electron-blocking layers

The research team proved through experiments and simulations that blue-green LEDs with p-type EBL had great potential in optoelectronic devices. Through simulation, the team found that p-AlGaN EBL inside the N-polar LED could better block the overflow of electrons, and it was easier for hole to be injected into MQWs. Thus, the turn-on voltage of N-polar LEDs would be lower. Through experiment, when adding forward bias to two pairs of MQWs, the MQW of blue-green LEDs had main wavelength around 480nm [8].

The research team embedded p-type Mg<sub>0.15</sub>Zn<sub>0.85</sub>O EBL between layers of MQWs and p-type Mg<sub>0.1</sub>Zn<sub>0.9</sub>O, and then they studied the effect of p-type MgZnO EBL toward optical and electrical characteristics of MgZnO/ZnO MQWs LED. At 60 mA, through adding Mg<sub>0.15</sub>Zn<sub>0.85</sub>O EBL, the ultraviolet emission is increased by 111.2%, and the ZnO LEDs' broad deep-level emission is also decreased. With a better ZnO LEDs' carrier distributions and structures, the research result showed p-type Mg<sub>0.15</sub>Zn<sub>0.85</sub>O EBL effectively limited the leakage of electron from MQWs to Mg<sub>0.1</sub>Zn<sub>0.9</sub>O, and it also increased the hole density in MQWs [9]. (24).

The research team numerically studied the optical and electrical features of GaN-based LEDs with different EBLs structures. The team found that using LEDs with p-InAlGaIn/GaN SL EBL, as shown

in Figure 4, can improve efficiency droop at high injection current density. The team also found GaN LEDs that adopted using p-InAlGaN/GaN SL as EBLs can realized the hole injection improvement and the electron leakage reduction when compared to GaN LEDs with rectangular p-AlGaN EBL [10].

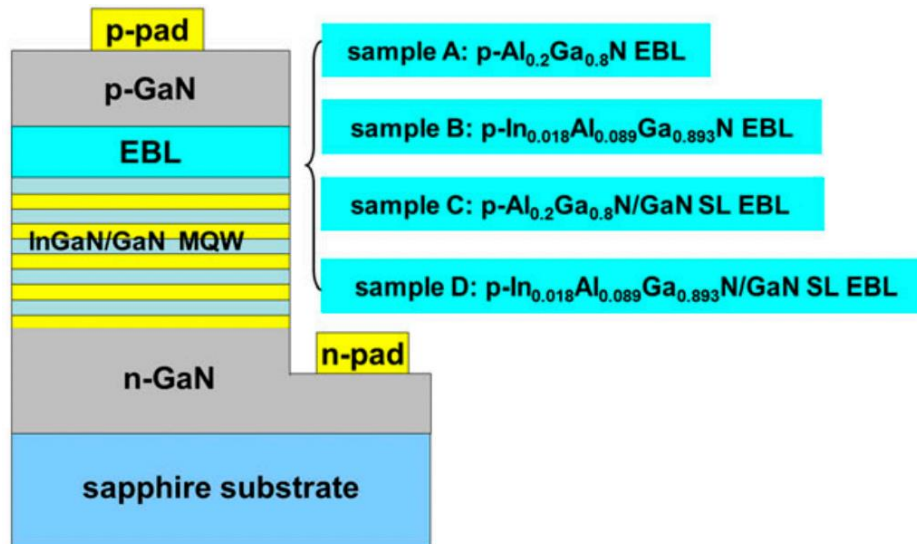


Figure 4. Schematic diagram with various composition of p-AlGaN/GaN SL EBLs [10]

### 2.3. Electron-blocking Layers with geometric shapes

The research team added grading double-side EBL into the AlGaN UV-LEDs, which could help UV LEDs to have better photoelectric performance under huge current density. Compared to traditional single composition structure, EBL with grading double-side can better increase the injection of holes, eliminated partial electrostatic field in the active region, and limit the leakage of electrons. As shown in Figure 5, both the LED B (double sided step grade) and the LED C (double sided linear graded) have higher electron concentration than the LED A with conventional design. By conducting experiments, researchers found that EBL with grading double-side can improve the light output power by a factor of 5.63. At 200A cm<sup>2</sup>, efficiency droop can at most be reduced to 15% for UV LEDs with emission wavelength of 273nm [11].

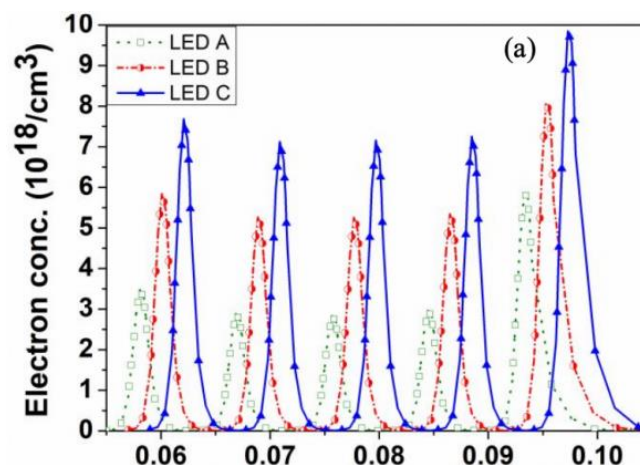
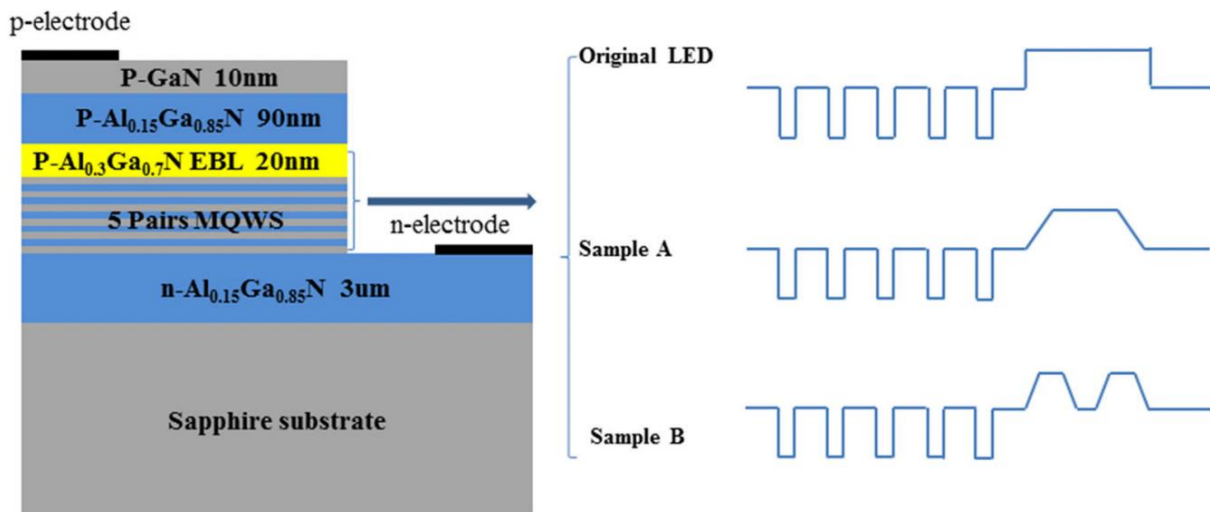


Figure 5. Electron concentration of double-side EBL of AlGaN UV-LEDs[11].

The team of authors used Trapezoidal EBL in Figure 6 to improve the overall function of UV-LEDs since Trapezoidal EBL has better photoelectric characteristics. By Conducting experiment, the team found that Trapezoidal EBL could effectively improve the electron confinement, radiative recombination, and hole injection rate, so using new structure can improve light output power by 26%.

At last, the team successfully improved light output power and internal quantum efficiency of UV LEDs [12].

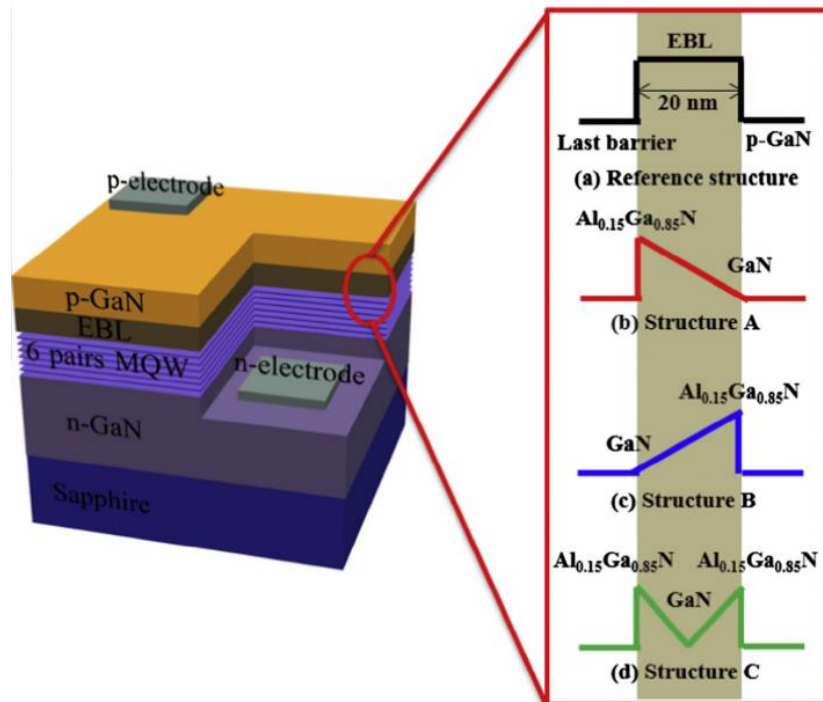


**Figure 6.** Sample A and B are the trapezoidal EBL[12]

The team of author designed a graded heart-shaped Al composition EBL in order to improve the light output power or DUV LED. This kind of structure overthrow the electrostatic field and reduced the downward bending of bands between EBL and the last quantum barrier. At last, the structure inhibited electron and current leakage. Using the SimuLED software, researchers conducted calculation for heart-shaped UV LED, and the result showed that the IQE was increased by a factor of 1.9 in contrast to traditional LEDs. In addition, at 20mA, the light output rate was increased by a factor of 2.1 [13].

This team of authors carried out the research about AlGaIn-based DUV LEDs with EBLs having changing concentration gradient of Al. EBLs with inverted-V-shaped performed higher carriers recombination and better light output power in contrast to traditional EBLs with unchanging Al composition. The team found that when carrier leakage can be greatly decreased, efficiency droop can therefore be improved. Thus, the mentioned research result could show that, appropriately changing Al composition inside LEDs can effectively improve the recombination rate of hole and electrons. Finally, due to the bend of energy band, hole injection efficiency and limitation of electrons were improved, which overall enhanced the recombination rate of LEDs [14].

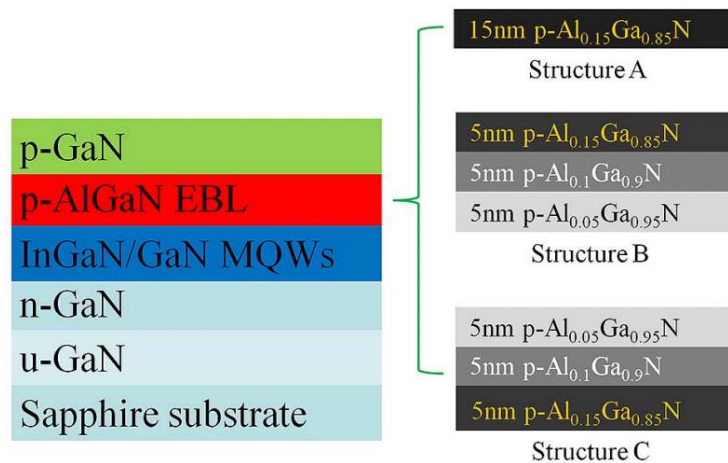
In this study, researchers numerically investigated AlGaIn EBL with graded Al compositions shown in Figure 7. Through elaborately designing growing direction along Al composition V-shaped grading EBLs, researchers wanted to reduce polarization effects so that they could improve electron confinement and hole injection. EBLs with growing direction along Al composition V-shaped grading can increase the output power by a factor of 2.5 as compared to that of LEDs with normal structures, while efficiency droop decreased at high currents. Furthermore, at 20 mA, forward current is reduced to 3.42V from 3.69V [15].



**Figure 7.** EBL with graded Al composition are shown in the right of the schematic graph [15]

For improving electron leakage and hole injection, the team of authors designed a tapered AlGaN EBL. First, the research team investigated some fundamental characteristics such as energy band diagram, carrier concentration, and electrostatic fields. Moreover, using data from simulations and experiments, the team studied GaN-based blue LEDs with step-graded aluminum composition and tapered AlGaN EBL. The result of simulation showed that the proposed tapered EBL can effectively enhanced hole injection and electron confinement, and LEDs with tapered EBL grown from metal-organic chemical vapor deposition showed 29% efficiency droop, which is 15% lower than original LEDs [16].

As shown in Figure 8, by inserting staircase EBL into the Blue InGaN Based LEDs and utilizing APSYS simulation software, the research team studied the mechanism of efficiency droop numerically. The research results showed that among the direction in which AlGaN were grown, gradually decreasing Al composition can decrease electron leakage and efficiency droop and improve LEDs' light output power. These evident performances originated from the modifications of energy bands, which can make electron blocking efficiency to be varied [17].



**Figure 8.** EBL with three-stepped staircase[17]

In order to improve the performance of LEDs, the team of author designed a sawtooth-shaped EBL. The team systematically investigated some basic characteristics such as the electron leakage, IQE,

and carrier concentration. Through the result of simulation, the research team find that higher output power and lower efficiency droop can be found on LEDs with sawtooth-shaped EBLs when compared to conventional AlGa<sub>0.3</sub>N EBLs, and this is because with appropriate amendments on EBL energy band, electron confinements and hole injection efficiency can be enhanced [18].

To improve the optic and electric performance of DUV-LED, the team of authors used lattice-matched AlInGaN quaternary superlattice EBL in the non-polar a-plane DUV-LED. To be specific, the research team increased the IQE of DUV-LED by 57.1%, and the light emission power was increased by a factor of 1.67 for SL EBL DUV-LEDs at 200mA. These results can be understood as improving the effective potential barrier of carriers. Thus, electron confinement ability and hole injection rate was enhanced, and the radiative recombination in the active region was improved [19].

#### 2.4. Electron-blocking Layers with mixed composition

The team of authors used undoped BAlN EBL to replace the traditional AlGa<sub>0.3</sub>N EBL in LED so that problems of p-doping can be reduced. Simulation result showed that adopting undoped BAlN EBL can effectively improve the concentration of hole, and such concentration was unrelated to the p-doping concentration. Compared to Al<sub>0.3</sub>Ga<sub>0.7</sub>N EBL with 10<sup>20</sup> cm<sup>-3</sup> doping concentration, undoped BAlN EBL can reduce efficiency droop to 5%, improve IQE by 2%, light out put power by 6% [20].

Through numerically investigating the tailored graded AlGa<sub>0.3</sub>N EBL shown in Figure 9, the research team evidently improved the light output of UV LED. Simulation showed that the occurrence of electron leaking into p-type layer can be eliminated when making appropriate change to the polarization field of the last potential barrier in the active region, and the hole injection of MQWs can also be enhanced. Moreover, The team explained how did the performance of UV LED be improved through aspects of, radiative recombination, simulated energy band diagram, and carrier concentration [21].

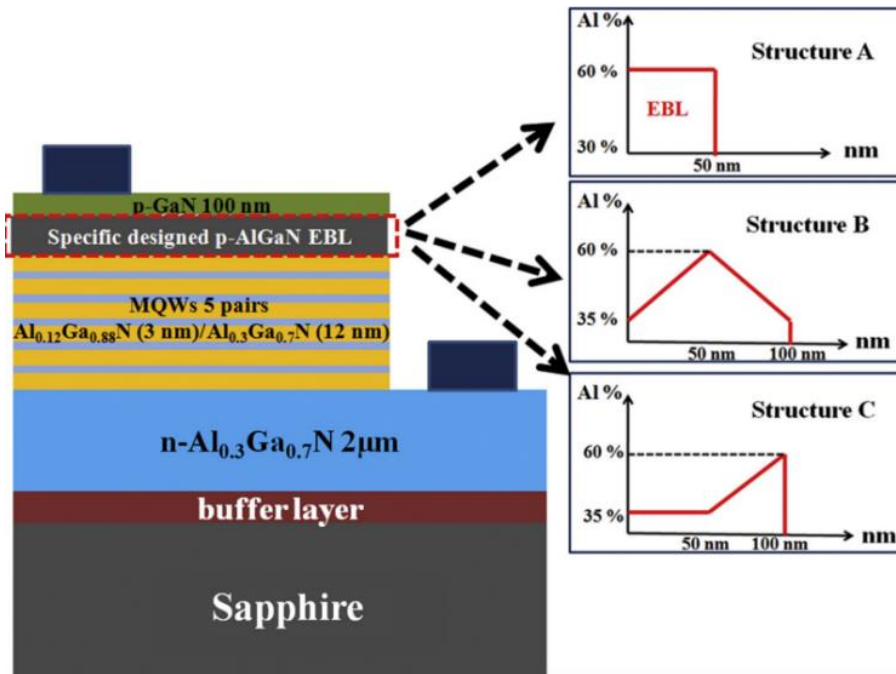
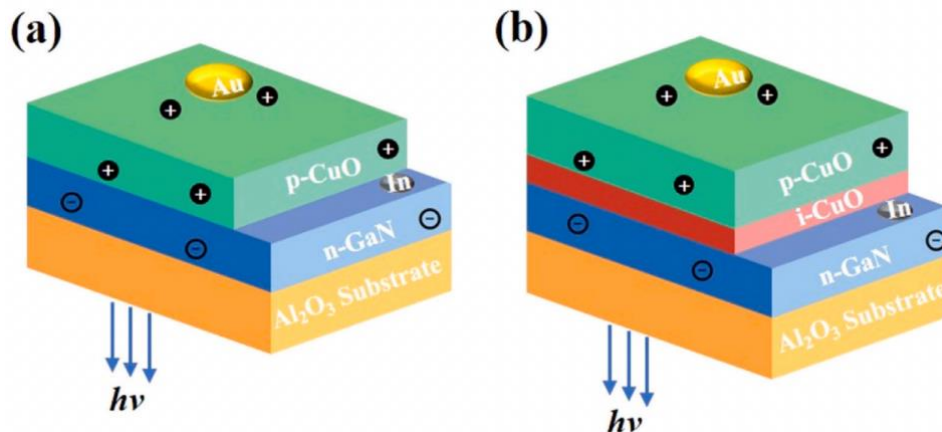


Figure 9. Structure B and C are the unique design of the research team [21]

The Research team deposited about 200nm high quality n-type ZnO film by respectively using sputtering powers of 25, 50, 100 W on the surface of AlnGa<sub>0.3</sub>N. Results of measurement, corresponding to AFM and RMS, showed that as the sputtering power of ZnO increased, the dislocation density decreased, and the grain size of it increased. Moreover, based on photoluminescence measurement, the team found that the sputtering power was correlated to the peak wavelength. Researchers added AlN EBL between GaN and ZnO film, which advanced the electroluminescence of n-ZnO side. When the sputtering power was at 25, 50, 100 W, the peak emission wavelength of LED was at 405, 390,

380nm. At last, by analyzing I-V curves, researchers realized the threshold voltage decreased as the sputtering power increased [22].

In Figure 10, the team of authors designed a near-white LED based on the structure of p-CuO/i-CuO/n-GaN heterojunction. The current I-V performance of the proposed structure showed a higher intensity and blue shift. Through analyzing I-V and the EBL performance, the team found that inserting CuO EBL could improve the stability of diodes, and the team also investigated the energy band diagram of two kinds of diodes. At last, the research team concluded p-CuO/n-GaN heterojunction with i-CuO EBL LEDs have strong potential of application in the aspect of WLEDs [23].



**Figure 10.** (a) and (b) are respectively the schematic graph of p-CuO/n-GaN EBL with or without i-CuO [23]

The research team investigated inserting composited electron blocking layers to increase the light output power. The team created CEBL by inserting a p-InGaN/GaN superlattice into AlGaIn layers, and they used simulation calculation to research such structure's effect on the improving UV LEDs. When the injection current was 350mA, CEBL could respectively improved internal quantum efficiency and light output power by 36% and 35.6%, and it effectively refined the height of the last quantum well, improved the hole injection efficiency, and averaged the carrier distribution[24].

The team of authors proposed a InGaIn/GaN green light LED with HEBL. Adding small amount of indium into normal AlGaIn EBLs, researchers successfully designed hybrid EBL. The team studied the effect of HEBL in and out practice. The team advanced ABCD model and simulated coefficient of ABCD. Reduction of the D value showed that HEBL limited the leakage of carriers. Simulation result showed that HEBL decreased holes' potential barrier, while it increased potential barrier of electrons. Therefore, more carrier could join in radiative recombination and be confined in MQWs. Thus, at 150mA, the light output power of HEBL LED is 80% higher than reference LED, and its outer quantum efficiency droop is also lower [25].

### 3. Conclusion

Over the past three decades, GaN-based LEDs were developed at a significant marvel speed. Many designs of EBL structures are proposed to improve the electron confinement in the active region, enhancing the hole injection rates and optimizing the carrier distributions. In this paper, we reviewed designs of EBL structures in GaN-based LEDs. It is expected that these optimization designs of EBL could bring LEDs with better performance and overall greater light output power.

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