Improvement of the efficiency droop of GaN-LEDs using an AlGaN/GaN superlattice insertion layer

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Abstract: With an n-AlGaN (4 nm)/GaN (4 nm) superlattice (SL) inserted between an n-GaN and an InGaN/GaN multiquantum well active layer, the efficiency droop of GaN-based LEDs has been improved. When the injection current is lower than 100 mA, the lumen efficiency of the LED with an n-AlGaN/GaN SL is relatively small compared to that without an n-AlGaN/GaN SL. However, as the injection current increases more than 100 mA, the lumen efficiency of the LED with an n-AlGaN/GaN SL surpasses that of an LED without an n-AlGaN/GaN SL. The wall plug efficiency of an LED has the same trend as lumen efficiency. The improvement of the efficiency droop of LEDs with n-AlGaN/GaN SLs can be attributed to a decrease in electron leakage due to the enhanced current spreading ability and electron blocking effect at high current densities. The reverse current of LEDs at –5 V reverse voltage decreases from 0.2568029 to 0.0070543 μA, and the electro-static discharge (ESD) pass yield of an LED at human body mode (HBM)-ESD impulses of 2000 V increases from 60% to 90%.

Key words: n-AlGaN/GaN superlattices; wall plug efficiency; droop; reverse current

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1. Introduction

GaN-based light-emitting diodes (LEDs) have attracted great interest because of their applications in full-color displays, full-color indicators and high-efficiency lamps. As injection current increases, the efficiency of an LED decreases, which is called the "droop" of LEDs[1]. The physical origin of efficiency droop remains under discussion. Electron leakage[2], low hole injection efficiency[3], carrier delocalization[4], Auger recombination[5], defects[6], junction heating[7] and non-uniform current spreading[8] have been suggested as explanations. It is investigated that the current crowding effect causes the droop of the optical output power, non-uniform luminance distribution, high junction temperature and a decrease in the LED's lifetime and ESD (electro-static discharge)[8, 9]. Different electrode pad structures have been used to improve current spreading, but the metallization electrode severely absorbs the light[10, 11]. In the work, we adopt an n-AlGaN/GaN superlattice insertion layer between an n-GaN and InGaN/GaN multiquantum well (MQW) active layer to improve current spreading without light absorption. Furthermore, the n-AlGaN/GaN superlattice (SL) can also block the electron at a high injection current in order to reduce the leakage current[12] and the droop of GaN-based LEDs has been improved greatly.

2. Experiment

The InGaN/GaN blue light LEDs were grown on c-plane (0001) oriented sapphire substrate with a Veeco metal-organic chemical vapor deposition (MOCVD) system using a high speed rotating disk with a vertical gas-flow growth chamber. Trimethylgallium (TMGa), trimethylindium (TMIn), triethylgallium (TEGa), trimethylaluminium (TMAl) and ammonia (NH_3) are used as source materials of Ga, In, Al and N, respectively. Silane (SiH_4) and biscyclopentadienyl magnesium (Cp_2Mg) are used for n-type and p-type dopant precursors. H_2 and N_2 are used as the carrier gasses.

First, the sapphire was annealed at 1100 ℃ in H_2 atmosphere to clean the surface, then after cooling down the reactor and nitride, the substrate in NH_3 at 550 ℃. A 20 nm thick GaN nucleation layer was deposited at 550 ℃, then the temperature increased to 1050 ℃ to grow a 2 μm thick undoped-GaN layer, followed by a 2 μm Si-doped n-type GaN layer ($n = 5 \times 10^{18}$ cm^{-3}). Then five periods of n-AlGaN (4 nm)/GaN (4 nm) superlattices (SLs) were grown. The Al composition in the AlGaN is 20%. The pressure for n-AlGaN/GaN superlattice

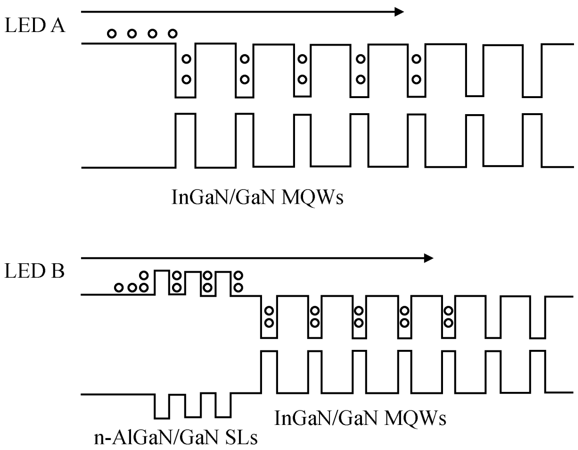

Fig. 1. LEDs with and without n-AlGaN/GaN SLs.

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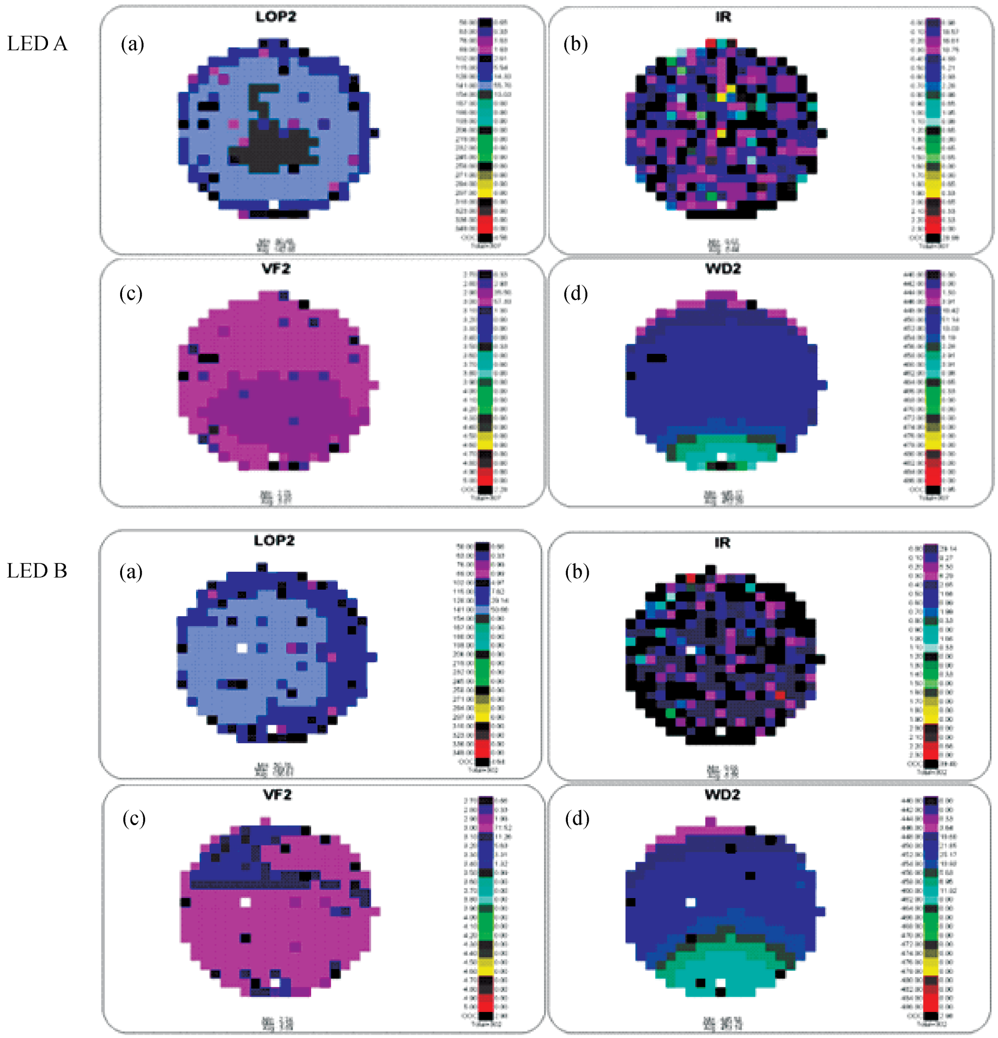

Fig. 2. Quick sorting test results of LEDs A and B.

growth is 50 Torr. The active layer consists of 7 pairs of InGaN (3 nm)/GaN (12 nm) multi-quantum wells. The first four quantum barriers were slightly SiH_4 doped ($n = 3 \times 10^{17}$ cm^{-3}). A 20 nm thick Mg-doped p-AlGaN (Al composition is 20%) used as electron blocking layer, followed by 120 nm thick p-GaN layer contact layer. A conventional LED structure without an n-AlGaN/GaN SL insertion layer at the same conditions was grown for comparison. The conventional LED structure was listed as LED A, the LED structure with the n-AlGaN/GaN SLs insertion layer listed as LED B. The structures of LEDs A and B are shown in Fig. 1.

3. Results and discussion

Figure 1 shows the current spreading and electron blocking effect of n-AlGaN/GaN SLs. In LED B, before the electrons inject into the InGaN/GaN MQW active layer, the n-AlGaN/GaN SLs block the electrons and make it uniformly distributed in the SLs. In LED A, the electrons inject into the active layer directly, without the blocking effect of n-AlGaN/GaN SLs. So the current leakage of LED A is more severe than that of LED B.

LEDs were fabricated using a conventional mesa structure method. Inductively coupled plasma (ICP) dry etching was used for 0.8-μm-deep etching to expose the n-GaN. Ti/Al/Ti/Au metal contacts were deposited onto the exposed n-GaN layer to serve as the n-type electrode. The contacts were thermally annealed in nitrogen ambient at 600 ℃ for 5 min. E-beam evaporation was used for indium tin oxide (ITO) layer deposition to serve as a transparent conducting layer of p-GaN. After the fabrication process, the processed wafers were thinned down to 90 μm for dicing into separate chips with a dimension of 1 × 1 mm^2.

Figure 2 shows the quick sorting test results at 350 mA before package of LEDs A and B, respectively. All the test results are listed in Table 1. We can clearly see from Fig. 2 that the light intensity, I_R, voltage and peak wavelength are uniformly distributed. Compared to LED A, the light intensity of LED B decreases at 350 mA because the voltage of LED B is a little

Table 1. Quick sorting test results of LEDs A and B.

LED	Light intensity (a.u.)	I_R (μA)	Voltage (V)	Peak wavelength (nm)
LED A	142.0779	0.4431	3.0110	452.2885
LED B	136.6063	0.2453	3.0918	453.7389

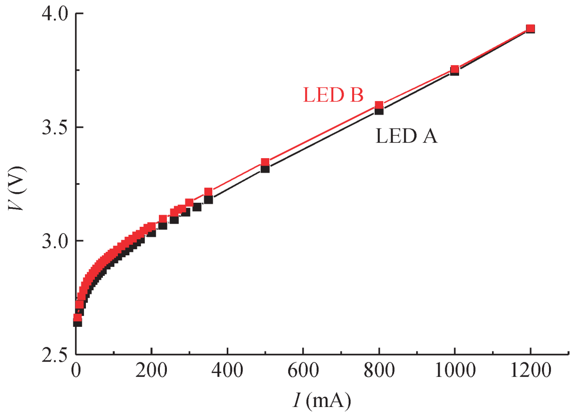

Fig. 3. Current–voltage (I–V) curves of LEDs A and B.

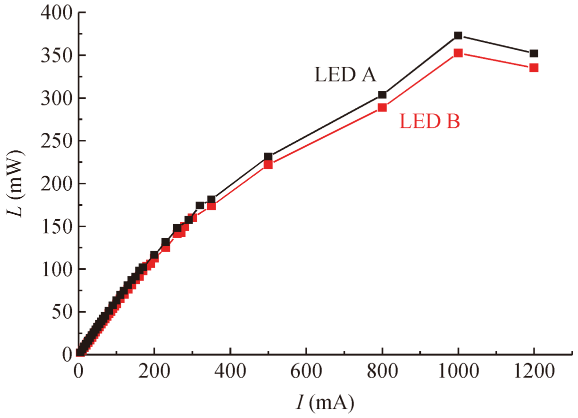

Fig. 4. L–I curves of LEDs A and B.

higher than that of LED A, which is caused by the higher resistance of the n-AlGaN/GaN SLs. The I_R of LED B decreases from 0.4431 to 0.2453 μA. The peak wavelength difference of LED A and LED B is only 1.5 nm, which can be neglectable.

The current–voltage (I–V) characteristics of LED A and LED B with the same chip size were measured at room temperature, as shown in Fig. 3. The operating voltage increases with the injection current. The forward voltage of LED B is slightly higher than that of LED A. The voltage of LED A at 350 mA is 3.18 V, and that of LED B is 3.258 V. The increment in forward voltage in LED B with an n-AlGaN/GaN SL is attributed to low electron concentration in n-AlGaN/GaN SLs due to a higher Si activation energy for the n-AlGaN layer as compared to n-GaN. Optimization of the doping profile of n-AlGaN/GaN SLs will decrease the voltage of LED B.

The light output powers of the packaged LEDs were measured in an integrating sphere at room temperature in an AC current mode with a pulse duration of 1 ms to eliminate the heating effect. Figure 4 shows the light output power of LEDs A and B as a function of injection current. The L–I curves show that the light output powers of LEDs A and B increase with the injected current and saturate at about 1000 mA. At the same injection current, the output power of LED A is a little higher than that of LED B. At an injection current of 350 mA, the light output powers of LED A and LED B are 181.3 and 173.4 mW, respectively. This is because the high resistance of the n-AlGaN/GaN SLs degraded the performance of LED B.

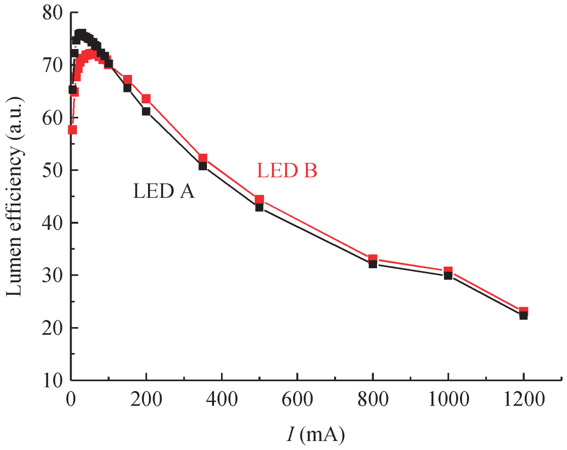

Fig. 5. Lumen efficiency of LEDs A and B at different injection currents.

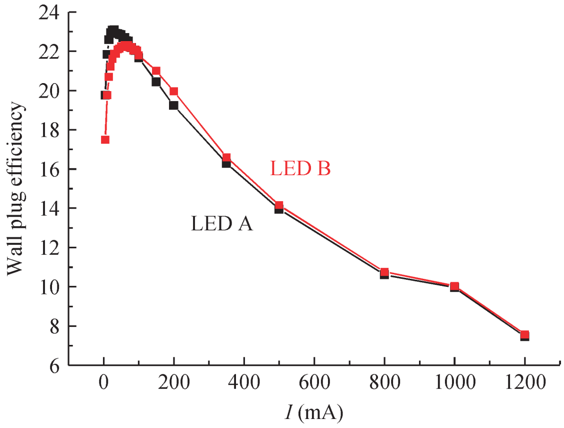

Fig. 6. WPE of LEDs A and B at different injection currents.

Figure 5 is the measured lumen efficiency for LEDs A and B. The maximum lumen efficiency of LED A was 76 a.u. at 30 mA, and LED B was 72 a.u. at 60 mA. Over the peak current, the lumen efficiency decreased monotonously with increasing operating current. When the injection current is lower than 100 mA, the lumen efficiency of the LED with n-AlGaN/GaN SLs is relatively lower compared to that of an LED without n-AlGaN/GaN SLs. However, as the injection current increases more than 100 mA, the lumen efficiency of LED B surpasses that of LED A, and the lumen efficiency of LED B is 3% higher than that of LED A at 350 mA. At 350 mA, the lumen efficiency of LED A is only 65% of that at 30 mA, compared to 74% of that of LED B. The droop of LED B is improved compared with that of LED A[12−14].

Figure 6 shows the WPEs of LED A and LED B at different injection currents. The maximum WPE of LED A is 23.5% at 30 mA, and 22.5% at 70 mA for LED B. Over peak current, the WPE of LED A and LED B decreases monotonously with increasing operating current. When the injection current is lower than 90 mA, the WPE of the LED with n-AlGaN/GaN SLs is relatively lower compared to that without n-AlGaN/GaN SLs. However, as the injection current increases more than 90 mA, the WPE of LED B surpasses that of LED A. Yen[12] calculated the current distribution of LEDs with APSYS simulation software, with an n-type AlGaN layer below the active region, the simulation results suggest that the distribution of electrons and holes within the active region is more uniform and the electron leakage current is markedly suppressed when the LEDs have an n-type AlGaN layer. Therefore, the efficiency and output power can be markedly improved at high current.

The I_R of LED A and LED B at –5 V reverse voltage (V_R) are 0.2568029 μA and 0.0070543 μA, respectively. The I_R of LED B decreased two orders of magnitude than that of LED A, which is attributed to the n-AlGaN/GaN SL insertion layer suppressing the propagation of dislocations. As the leakage current of LEDs is strongly related to their lifetime, it is clear that the life time of LED B is much longer than that of LED A.

The ESD characteristics of the LED were tested by HBM and the ESD pulse is 2000 V. After the ESD test, we applied a reverse bias of 5 V to the LEDs, after which we measured the leakage current. In cases where the leakage current was higher than 1 μA, we concluded that the LEDs had failed. Compared with 50%–60% average ESD pass yield of LED A, the LED B has a higher pass yield of more than 90% after HBM-ESD impulses of 2000 V were applied to the LED chips. The current spreading of LED B is much better than that of LED A, so the current generated by ESD will be released.

4. Conclusion

With n-AlGaN (4 nm)/GaN (4 nm) SLs inserted between n-GaN and InGaN/GaN MQWs, the efficiency droop of GaN-based LEDs have been improved. At a low injection current, the lumen efficiency and WPE of LEDs with n-AlGaN/GaN SLs are lower than that without n-AlGaN/GaN SLs, but when the injection current increases to 100 mA, the lumen efficiency and WPE of LEDs with n-AlGaN/GaN SLs surpass that of LEDs without n-AlGaN/GaN SLs. The improvement in efficiency droop of the LEDs with n-AlGaN/GaN SLs can be attributed to the decrease in electron leakage due to the enhanced current spreading ability and electron blocking effect at high current densities. The reverse current I_R of LEDs at –5 V reverse voltage (V_R) has improved from 0.2568029 to 0.0070543 μA. The ESD pass yield of LED at HBM-ESD impulses of 2000 V increases from 60% to 90%.

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