Improved III-nitrides based light-emitting diodes anti-electrostatic discharge capacity with an AlGaN/GaN stack insert layer*

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Abstract: Through insertion of an AlGaN/GaN stack between the u-GaN and n-GaN of GaN-based light-emitting diodes (LEDs), the strain in the epilayer was increased, the dislocation density was reduced. GaN-based LEDs with different Al compositions were compared. 6.8% Al composition in the stacks showed the highest electrostatic discharge (ESD) endurance ability at the human body mode up to 6000 V and the pass yield exceeded 95%.

Key words: AlGaN/GaN stacks; light-emitting diodes; dislocation density; ESD
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1. Introduction

In recent years III-nitrides based light-emitting diodes (LEDs) have attracted more and more academic and industrial effort and enthusiasm, due to their wide applications in many places needing illumination, especially in liquid crystal display (LCD) back lighting, mobile phone back lighting, vehicle head lights and, of most importance, general illumination. Bad reliability especially anti-electrostatic discharge (ESD), is a key obstacle for LED penetration into these applications. Many researchers have proposed different techniques to solve the problem, Jeon *et al.*[1] inserted internal capacitance to improve ESD, Chiang *et al.* and Su *et al.*[2, 3] both proposed an n-GaN current spreading layer to improve ESD, Chang *et al.*[4] designed a GaN Schottky diodes with a chip process to increase ESD, Jang *et al.*[5] considered that p-AlGaN could fill some dislocation-related pits and thicker p-AlGaN could suppress pits and improve ESD. We concluded that a high dislocation density induces a poor epilayer quality, which then reduces the luminous efficiency and ESD capability. We therefore propose a AlGaN/GaN stack layer insert between the u-GaN and n-GaN in the LED's structure to reduce the dislocation density in the further epilayer and improve the material's quality as well as ESD endurance. The material properties and the ESD performance of the LEDs were studied.

2. Experiment procedure

The GaN-based blue InGaN/GaN LEDs were grown on c-plane (0001) oriented sapphire substrates with an Aixtron G5HT planetary metal-organic chemical vapor deposition (MOCVD) system. The Ga and Al sources for the GaN and AlGaN were trimethylgallium (TMGa) and trimethylaluminium (TMAl), respectively, while the In and Ga sources for the multi-quantum wells (MQWs) were trimethylindium (TMIn) and triethylgallium (TEGa). Ammonia (NH_3) was used as the N source. The n-type and p-type dopant precursors were silane (SiH_4) and biscyclopentadienyl magnesium (Cp_2Mg), respectively. Purified H_2 and N_2 were used as carrier gases for growing the GaN and MQWs. The growth procedure was as follows: first, the sapphire substrate was heated up to 1080 ℃ in H_2 atmosphere to clean the surface of contaminants, then the surface temperature was ramped down to 560 ℃ and deposited a 30 nm GaN nucleation layer, after nucleation the temperature was raised to 1020 ℃ for GaN recrystalization and coalescence, a 3 μm-thick unintentionally doped GaN (u-GaN) layer was grown, and then 20 pairs of AlGaN/GaN stacks with thicknesses of 16 nm and 6 nm, respectively, were grown at 100 mbar and the Al/Ga ratio varied for comparison, followed by a 2 μm Si-doped n-type GaN layer ($n = 5 \times 10^{18}$ cm^{-3}), which was grown at 1050 ℃ with reactor press 600 mbar. Then 10 pairs of InGaN/GaN MQWs were grown at 400 mbar with InGaN QW (3 nm)/GaN QB (14 nm). A 20 nm p-AlGaN electron blocking layer doped with Mg about 2×10^{19} cm^{-3} and 200 nm p-GaN doped with Mg about 4×10^{19} cm^{-3} for hole injection and a 10 nm p-GaN cap layer for contact were grown at 900 ℃ and 200 mbar. The whole structure was then annealed at 700 ℃ in N_2 atmosphere for 600 s. A conventional LED structure without an AlGaN/GaN stack was grown for comparison. Three AlGaN/GaN stack samples of the same growth condition with different Al/Ga ratios were also grown on a GaN template to conform the accurate Al composition. The detailed Al/Ga ratio of the above four LED samples are listed in Table 1.

Furthermore, two GaN samples with and without AlGaN/GaN stacks on uGaN/sapphire were grown to compare the dislocation density. After GaN growth, the two samples were dipped into the melting NaOH for about 3 min and the etching pits were formed.

The as-grown AlGaN/GaN stacks were characterized with a Bede D1 high-resolution X-ray diffraction (HRXRD) system

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Table 1. Al/Ga ratio of four samples.

Sample	Al/Ga ratio
A	1.0
B	1.5
C	2.0
D	0

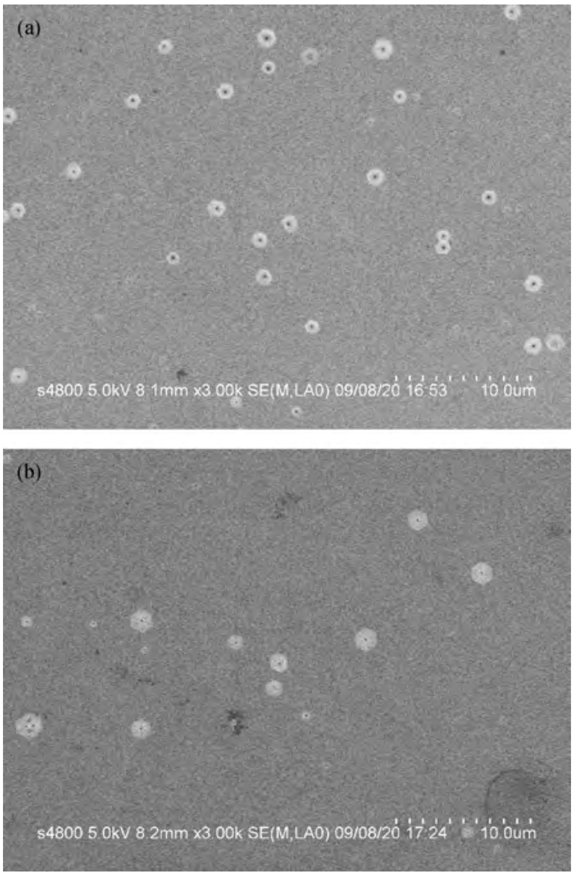

Fig. 1. SEM scan of etching pits of GaN (a) without and (b) with AlGaN/GaN stacks.

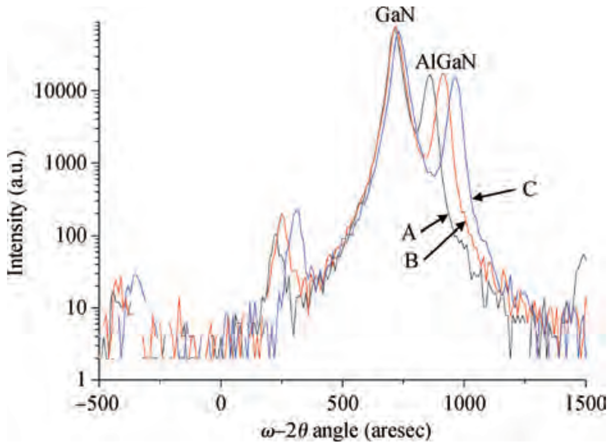

Fig. 2. XRD (0002) ω–2θ scan of stacks A, B, and C.

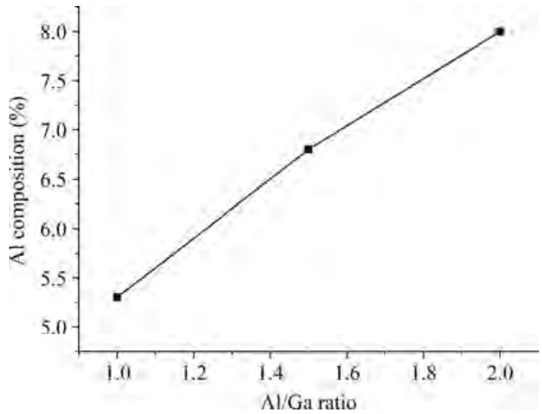

Fig. 3. Al composition varied with Al/Ga ratio.

to confirm the Al composition in the stack structures. A Hitachi S4800 field emission scan electron microscope (SEM) system was used to confirm the etching pit densities. The four LEDs were processed to 250 $\times$ 575 μm^2 LED chips with ITO as the p-GaN contact layer and Cr/Pt/Au as the n-GaN contact. The LEDs' ESD endurance abilities were measured using a Chroma-A581501 ESD test system with the ANSI/ESD STM5.1-2001 international standard, when the reverse current exceed 2 μA after ESD test the LEDs were considered to fail.

3. Results and discussion

Figure 1 shows the SEM image of the GaN morphology after etching in melting NaOH without and with AlGaN/GaN stacks, the etching pits decreased about by 50% after the AlGaN/GaN stack insert layer was used, which indicated that the threading dislocation density of the GaN epitaxial structure with AlGaN/GaN stacks was reduced and the material quality was improved greatly. This may be attributed to some dislocations being bent by tensile stress and merged with those dislocations with contrast horizontal vectors so the total dislocations reduced.

Figure 2 shows the XRD (0002) ω–2θ scan result of stack structures A, B and C. The scan result demonstrated that the AlGaN/GaN stacks were in tensile strain and when the Al/Ga ratio increased the AlGaN peak became larger, which indicated the Al composition in AlGaN/GaN stacks became higher. We can calculate the Al composition according to Vegard's law as follows to confirm the result:

$$d_{\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}} = d_{\mathrm{AlN}}x + d_{\mathrm{GaN}}(1-x). \tag{1}$$

Figure 3 shows the Al composition change with varied Al/Ga ratio according to Vegard's law, we can clearly see that the Al composition almost increases linearly with Al/Ga ratio increasing.

Figure 4 shows the HBM 4000V ESD yield of LEDs with different Al composition stacks. LEDs A, B, C and D correspond to stacks A, B, C and D, respectively. The ESD endurance ability of LEDs A, B, C with AlGaN/GaN stacks has improved greatly compared with LED D without stacks. The ESD endurance ability increased with increasing Al composition at first, when the Al composition in the stacks was 6.8% (LED B) the ESD pass yield exceeded 90%, but when Al composition became higher, the ESD endurance ability decreased and the ESD pass yield of LED C reduced to about 60%. This may be attributed to the increase of tensile stress with Al composition and when the Al composition was higher the dislo-

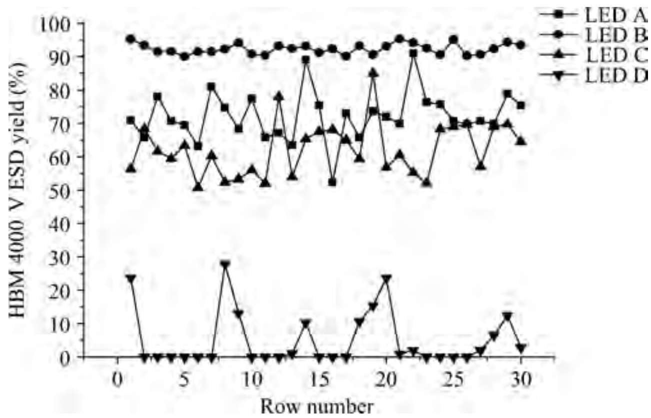

Fig. 4. ESD result of 250 × 575 μm^2 chip.

cation was reduced and improved the ESD endurance ability. However, when the Al composition was too high, a too large tensile strain would decrease the LED's quality and make the epilayer micro-crack, which reduced the LED's ESD endurance ability.

Figure 5 shows a typical HBM 6000V ESD test mapping result of LEDs with stacks B, the ESD pass yield still exceeded 95% and even the reverse ESD voltage was as high as 6000 V, which is one of the best ESD endurance abilities of GaN-based LEDs ever reported.

4. Conclusions

A LED structure with an AlGaN/GaN stacks layer was proposed to improve ESD endurance ability. An AlGaN/GaN stacks insert layer increased the tensile strain of the epilayer and reduced the dislocation density, which improved the GaN-based LED's ESD endurance ability, a 6.8% Al composition of the stacks increased the LED's HBM ESD endurance ability up to 6000 V and the pass yield exceeded 95%. When the Al composition was too high, the LED's ESD endurance ability was reduced.

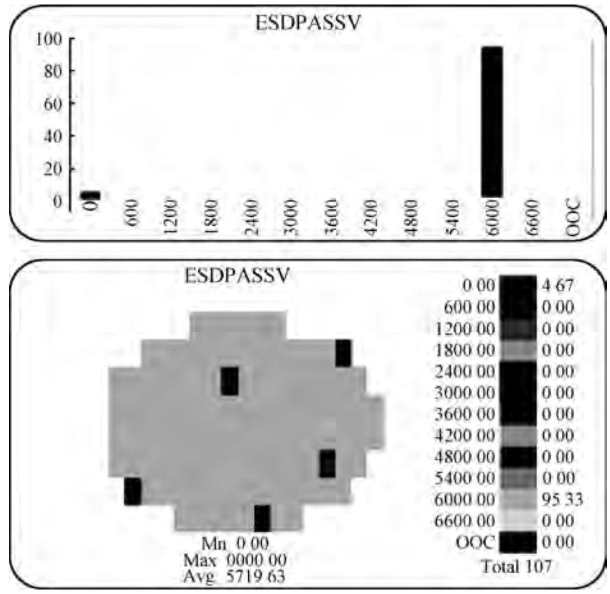

Fig. 5. ESD mapping of LED with stack B.

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