Improved ESD characteristic of GaN-based blue light-emitting diodes with a low temperature n-type GaN insertion layer

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Abstract: We demonstrate the improvement of the electrostatic discharge (ESD) characteristic of GaN-based blue light-emitting diodes (LEDs) by inserting a low-temperature n-type GaN (LT-nGaN) layer between the n-type GaN layer and InGaN/GaN multiple quantum wells (MQWs). The ESD endurance voltage > 4000 V pass yield is increased from 9.9% to 74.7% when the LT-nGaN insertion layer is applied to the GaN/sapphire-based LEDs. The LT-nGaN plays a role of buffer layer for MQWs, which reduces the strain of MQWs and improves the interface quality. Moreover, we also demonstrate that ESD characteristics of the LEDs with LT-nGaN insertion layer growth in N_2 are much better than that in H_2, which further confirm that the improvement of ESD characteristics is due to the strain relaxation in MQWs. Optoelectrical measurements show that there is no deterioration of the electrical properties of LEDs and the light output power of LEDs at an injection current of 20 mA is improved by 13.9%.

Key words: MOVPE; LED; GaN; electrostatic discharge (ESD)

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1. Introduction

In recent years, high brightness GaN-based light-emitting diodes (LEDs) grown by metalorganic vapor phase epitaxy (MOVPE) have stimulated a great deal of interest[1−13]. Generally, the light output power of LEDs depends on the internal quantum efficiency (IQE) and the light extraction efficiency (LEE)[3]. The former case mainly relies on the quality of MQWs and their heterointerfaces within the active region. The performance of InGaN/GaN MQWs is limited by several factors. First of all, the MQW stack is under considerable strain due to the large difference in the lattice and thermal constant between the InGaN quantum wells and the GaN barriers. This strain generates a piezoelectric field inside the MQW stack, which results in a quantum confined Stark effect (QCSE)[4, 5]. In addition, the n-GaN layeris conventionally grown at high temperature (∼1050 ℃) in H_2 atmosphere, whereas the InGaN/GaN MQWs are grown at 750 ℃ in N_2 atmosphere. Such a high temperature gradient ($\Delta T = \sim 300$ ℃) may lead to a poor interface between the n-GaN template and the InGaN/GaN MQWs. Therefore, it is very possible that a large number of nonradiative recombination centers are generated at the interface[6]. Both the strain and the poor interface will deteriorate the LED performance such as the electrostatic discharge (ESD) characteristics and the light output power[7].

The growth of the insertion layer between the MQWs active layer and the n-GaN cladding layers, such as an InGaN underlying layer and a short-period InGaN/GaN superlattice strain-relief layers, are widely used to improve the performance of GaN-based blue LEDs[7−10]. The purpose of the insertion layer is to improve the crystal quality and to release the strain status of MQWs. The design of growth conditions of this layer such as growth temperature, thickness, and doping level is very important for the LED performance. In this paper, a low temperature n-GaN (LT-nGaN) layer is inserted between the InGaN/GaN MQWs active layer and the n-GaN template, and the effect of silicon doping level and growth atmosphere of the LT-nGaN layer on the performance of GaN-based blue LED is also investigated.

2. Experiment

The LED samples used in this study were all grown on c-face (0001) 2-inch sapphire substrates in a vertical flow 56 × 2” planetary system. Ammonia was used as a nitrogen precursor. For elements of group III trimethylgallium (TMGa) and trimethylindium (TMIn) were used as precursors for gallium and indium, respectively. Doping of n- and p-type layers was done using silane and biscyclopentadieny magnesium (Cp_2Mg), respectively. Figure 1 shows the schematic layer

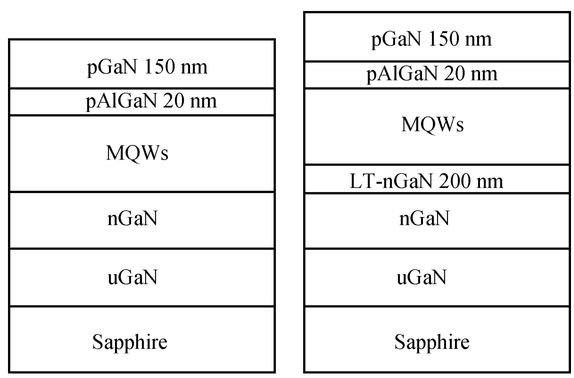

Fig. 1. Schematic layer structure of the GaN-based LEDs without and with an LT-nGaN insertion layer.

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Table 1. LED Samples with an LT-nGaN insertion layer at different conditions.

Sample	Description	LT-nGaN doping (cm^{-3})	LT-nGaN growth atmosphere
LED A	Conventional LED	—	—
LED B	With LT-nGaN	5×10^{17}	N_2
LED C	With LT-nGaN	1×10^{18}	N_2
LED D	With LT-nGaN	5×10^{18}	N_2
LED E	With LT-nGaN	1×10^{18}	H_2

structure of the GaN/sapphire-based LEDs without and with the LT-nGaN insertion layer. The conventional LED structure, which consisted of a 25-nm-thick GaN nucleation layer, a 2-μm-thick undoped GaN layer, a 2-μm-thick highly doped n-type GaN layer, 14 pairs of $In_{0.11}Ga_{0.89}N$ (3 nm)/GaN (14 nm) MQWs, a 20-nm-thick p-AlGaN layer, and a 150-nm-thick p-type GaN layer, was labeled as LED A. In addition, the LEDs with a LT-nGaN insertion layer in N_2 atmosphere doped with 5×10^{18} cm^{-3}, 1×10^{18} cm^{-3}, and 5×10^{17} cm^{-3} were labeled as LED B, LED C, and LED D, respectively. For the comparison of growth atmosphere, an LED with a LT-nGaN insertion layer growth in H_2 atmosphere was labeled as LED E with the same silicon doping as LED B. Details of growth conditions of all LED samples are shown in Table 1. In the LED chip fabrication process, LEDs with a dimension of 1035 $\times$ 1035 μm^2 were fabricated using standard LED processing techniques. Firstly, the p-GaN layer and the MQW active regionwere partially etched until the n-GaN layer was exposed. Next, indium tin oxide (ITO) was deposited onto the p-GaN surface as the transparent contact layer (TCL) by an electron beam evaporator. In addition, Cr/Au was deposited on the exposed n-GaN layer and ITO layer to serve as the metal electrodes.

In this study, to investigate the quality of the MQWs and their impact on the LED devices, the LED samples were measured using high resolution X-ray diffraction (BEDE D1 X-ray system) and PL (Nanometrics RPM BULE 2000). He-Cd laser with a wavelength of 325 nm was used to serve as the PL exciting source. The ESD characteristics of the LED samples were measured by an electro-tech system ESD simulator (Model 910). The ESD simulator can produce electrical pulses similar to those emitted by a human body. We started the ESD test using a negative bias of 300 V on the LED samples and then gradually increased the ESD pulse amplitude with a step of 500 V. After each testing phase, we applied a reverse bias of 5 V to the LEDs and measured the leakage current. In cases where the leakage current was higher than 2 μA, we concluded that the LEDs had failed. In this way, we obtained the yield of ESD > 4000 V of all LED samples.

3. Results and discussion

Figure 2 shows the ESD > 4000 V yield of LED A, LED B, LED C, and LED D. It can be clearly seen that the ESD characteristics of GaN-based LEDs are significantly enhanced by inserting a LT-nGaN layer between the n-GaN buffer layer and the InGaN MQWs. With a LT-nGaN layer at a silicon doping level of 1×10^{18} cm^{-3}, we can obtain the highest level of 74.7% ESD > 4000 V yield of LEDs, which is much higher than that of LEDs without the LT-nGaN layer. The higher voltage endurance can be explained by strain relaxation for the following MQW growth based on the LT-nGaN buffer layer and the improvement of the heterojunction interface quality between LT-nGaN and InGaN MQWs[9]. In a conventional LED epi-structure, when the MQW active layer grown at a relatively lower temperature ($\sim$750 ℃) is simply deposited on a high-temperature-grown ($\sim$1050 ℃) n-GaN buffer layer, this greater growth temperature mismatch ($\Delta T = 300$ ℃) will produce large thermal strain in MQWs[6–9]. In addition, greater growth temperature difference needs more interruption time, which may cause more decomposition of the surface layer, leading to a bad interface quality between n-GaN and InGaN MQWs. Subsequently, defects such as nitrogen vacancies are generated[6]. This poor interface between MQWs and the n-GaN buffer, especially the generated defects, is the weakest points for LEDs in the ESD test. In our experiment, the LT-

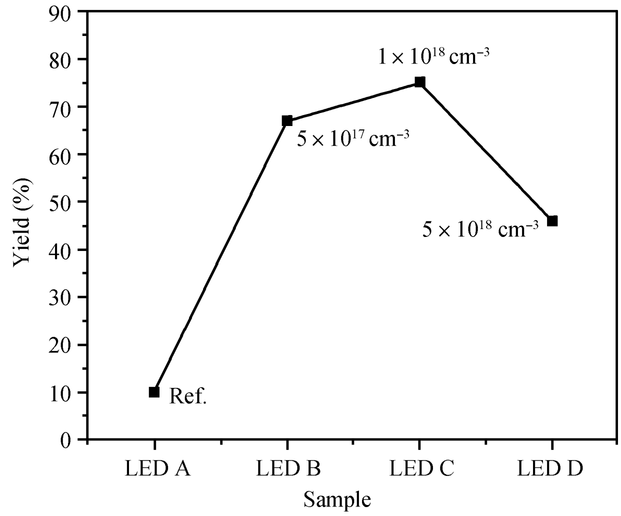

Fig. 2. ESD > 4000 V yield of LEDs without and with an LT-nGaN insertion layer at different doping levels.

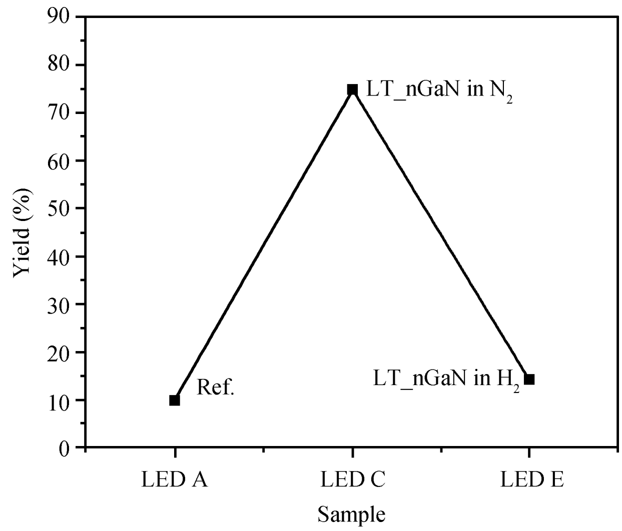

Fig. 3. ESD > 4000 V yield of LEDs without and with an LT-nGaN insertion layer at different growth atmospheres.

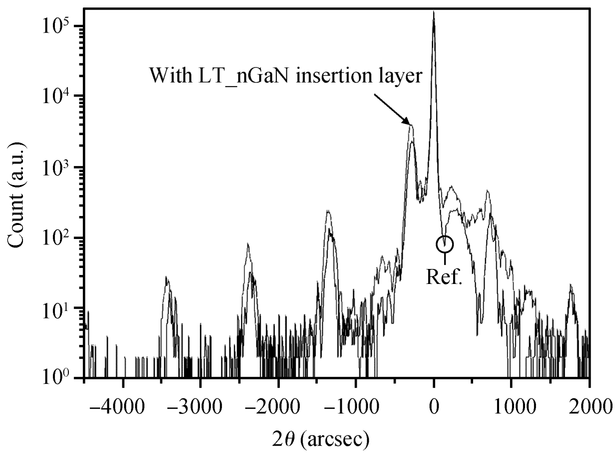

Fig. 4. (0002) ω–2θ X-ray diffraction (XRD) spectra of the reference LED (Ref.) and an LED with an LT-nGaN insertion layer.

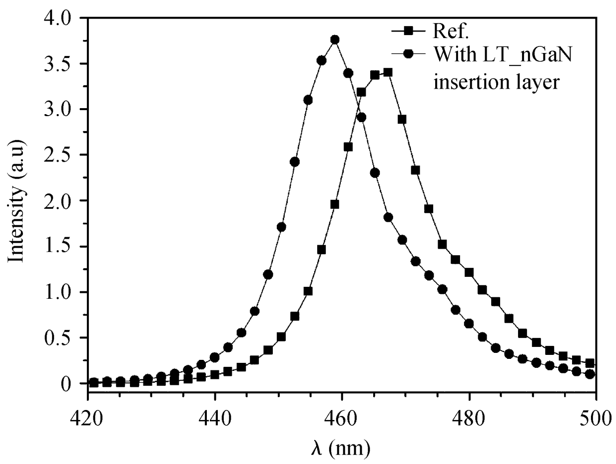

Fig. 5. PL spectra of the reference LED and the LED with an LT-nGaN insertion layer.

nGaN insertion layer, which was grown at a moderate temperature (~850 ℃) between MQWs and n-GaN growth temperature, can improve both the strain status of MQWs and the interface quality. In our design, the LT-nGaN layer plays a role of buffer layer for the following MQWs growth. By decreasing the thermal strain and the defects in the InGaN MQWs as well, the ESD characteristics of LEDs with LT-nGaN insertion are significantly enhanced compared with conventional LEDs. Furthermore, based on our results, slight silicon doping can enhance GaN crystal quality, which is beneficial for the improvement of LED ESD characteristics. However, when the amount of silicon doped in the LT-nGaN is too high, GaN crystal quality will be deteriorated. From this point of view, we can explain why ESD endurance characteristics decrease when doped silicon is increased from 1×10^{18} to 5×10^{18} cm^{-3}.

We know that the lattice orientation of GaN can be different in different atmospheres. So in this paper, we further investigate the impact of grown LT-nGaN buffer layer in H_2 atmosphere on the LED ESD properties. Figure 3 shows the ESD > 4000 V yield of LED A, LED C, and LED E. The results indicate that ESD yield varies greatly with LT-nGaN growth in different atmospheres, which indicates that LED

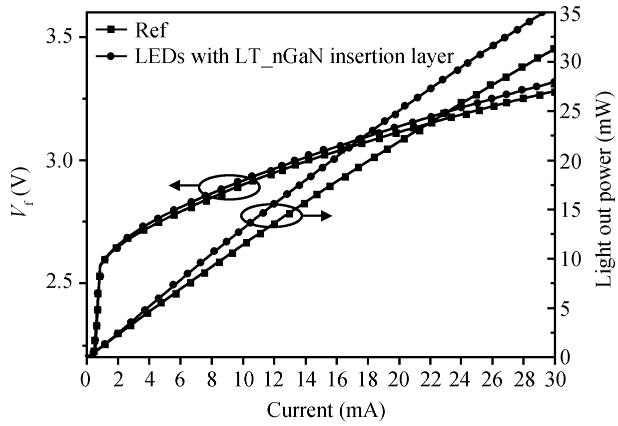

Fig. 6. LOP-I–V curves of the reference LED and the LED with an LT-nGaN insertion layer.

ESD endurance characteristics are very sensitive to the LT-nGaN growth atmosphere. The LED ESD characteristics with LT-nGaN growth in H_2 atmosphere are slightly better than that of the conventional one. However, compared to that of LEDs grown in N_2 atmosphere, the LED ESD yield is obviously decreased. When grown in N_2 atmosphere, the lattice orientation of LT-nGaN will be more similar to MQWs. It means that the strain in MQWs can be smaller with LT-nGaN growth in N_2 atmosphere than that in H_2 atmosphere. In this way, we can explain that the improvement of ESD characteristics is caused by the strain relaxation of MQWs with LT-nGaN growth in N_2 atmosphere. Therefore, we further confirm that the ESD characteristics with LT-nGaN insertion layer are due to the strain relaxation of MQWs. These analyses are also confirmed by the X-ray diffraction (XRD) and PL measurements.

Figure 4 shows the (0002) ω–2θ XRD spectra taken from LED A and LED C. The MQW satellite peak intensity of LEDs with LT-nGaN insertion layer is much higher than that of the reference LED, which indicates that the crystal quality of the following InGaN/GaN MQWs is much better. On the other hand, much clearer and sharper peaks of the MQW satellites indicate that the interface quality of MQWs is also improved.

Figure 5 shows the PL spectra of LED A and LED C. Results show that the PL intensity increases slightly with the LT-nGaN insertion layer. Moreover, compared with conventional LEDs, we can clearly see that the peak wavelength shifts from 466.5 to 463 nm. This blueshift of peak wavelength and increase of PL intensity confirm the reduction of quantum confined stack effect caused by the stress in MQWs. The PL intensity improvement is due to the better quality of grown MQWs based on an LT-nGaN buffer layer and the strain relaxation of MQWs as well.

In order to investigate the impact of the LT-nGaN buffer layer on the optoelectrical properties of LEDs, we test the I–V properties and light output power of LEDs. The results are shown in Fig. 6. By introducing the LT-nGaN layer, the operating voltage of LEDs at an injection current of 20 mA is slightly increased from 3.05 to 3.07 V. This small increase is due to the series resistance of the LT-nGaN layer. On the other hand, compared to LEDs without the LT-nGaN layer, the light output power of LEDs is enhanced by 13.9%. The improvement in the light output power is attributed to the reduction of the quantum confined stack effect caused by the stress and the better crystal quality in MQWs.

4. Conclusion

In summary, we have significantly enhanced the ESD characteristics of GaN-based blue LEDs by using an LT-nGaN layer inserted between the n-type GaN layer and the MQWs active layer. With a LT-nGaN layer at a silicon doping of 1×10^{18} cm^{-3}, the ESD > 4000 V yield has been improved from 9.9% to a best level of 74.7%.The LT-nGaN playsa role of buffer layer for MQWs, which can reduce the strain status of MQWs and improve the interface quality. Moreover, we have demonstrated that ESD characteristics of LED with LT-nGaN insertion layer growth in N_2 is much better than in H_2, which further confirm that the improvement of ESD characteristics is related to the strain relaxation in MQWs with LT-nGaN insertion layer. Both the XRD and PL measurements confirmed our analysis. Optoelectrical measurements show that there is no deterioration to the electrical properties of LEDs and the light output power of LEDs at an injection current of 20 mA is improved by 13.9%.

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