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Multilayer Epitaxial Lateral Overgrowth of Light Emitting Diode with Anisotropically Etched GaN/Sapphire Interface.

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1. Introduction

GaN-based light emitting diode (LED) has attracted great attention in last few years due to its importance in solid state lighting applications. The GaN-based devices are often epitaxially grown on sapphire. The as grown GaN epitaxial layer has high crystal dislocation density, typically in the range of $10^{8\text{-}10}$ cm^{-2}. These crystal defects are detrimental to optoelectronic device performance. The high refractive index of GaN restricts the escape angle of emitting light and results in low light extraction efficiency. Various surface texture [1], photonic crystal structure [2], and patterned substrate [3-5] methods have been investigated and demonstrated significant light extraction enhancement. A common feature in all these different methods is having large surface variations at the GaN-air or GaN-sapphire interface. The fabrication process often involves micro lithography and etching. Here, we report an innovative fabrication process that can significantly improves both the light extraction efficiency and crystal quality without the need of photolithography substrate patterning.

2. Experiments

The material epitaxial growth uses nominal low pressure metalorganic chemical vapor deposition (MOCVD). A 30 nm of low temperature GaN nucleation layer followed by a 2.5 µm GaN buffer layer was grown on (0001) sapphire template. The GaN wafer was then immersed in high temperature molten KOH at 280^{o}C for 12 minutes. The molten KOH selectively etched defect sites on GaN wafer surface and etched continuously downward opening up channels to sapphire interface. The molten KOH was led to GaN-sapphire interface through these self-assembled channel openings. The etching process then turned into lateral direction because the defect density was high at interface and etched away a thin layer of GaN along sapphire interface. It is known that KOH etching is typically anisotropic and preferentially etches specific crystallographic planes. Additional GaN was grown on the etched GaN wafer by MOCVD to fill up both the etched vertical openings and hexagonal surface pits to provide flat top surface for the subsequent LED device growth. The multilayer epitaxial lateral overgrowth (MELO) process was shown in Fig. 1. The dislocation bending, annihilation or forming loops followed the lateral growth direction. At the coalescence region would form new threading dislocations or stacking faults. Therefore, most of dislocation have been etched or even removed after the KOH etching process. Finally, the LED device structure was 3.5 um n-doped GaN, 10 pairs of $Al_{0.05}Ga_{0.95}N$/InGaN quantum wells (13 nm/2.5 nm), and 100 nm of p-doped GaN cap layer. The designed quantum well emission wavelength was at 394 nm.

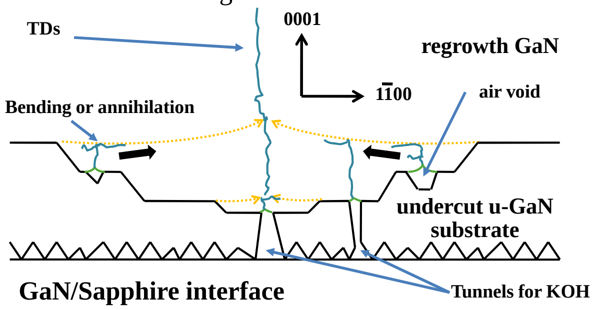

Fig. 1 Scheme of multilayer epitaxial lateral overgrowth

3. Results and discussion

The most general threading dislocations (F region) could be seen in Fig. 2. The dashed line indicates the u-GaN and LED regrowth interface. The G regions near dashed line exhibited some particular mechanism, which prevent the threading dislocation pass through the multiple quantum well along the growth direction. We could see the dislocation bent and annihilated in G_1 position, form stacking fault in G_2 position and loop in G_3 position. Besides, we also see the air void below the dashed line. It might result from the slower growth rate at inner sidewalls, thus the region would be buried in lateral overgrown GaN. The dislocation density at the bottom GaN layer is about 2.0×10^9 cm^{-2} and slightly reduces to 1.0×10^8 cm^{-2} at the top GaN layer

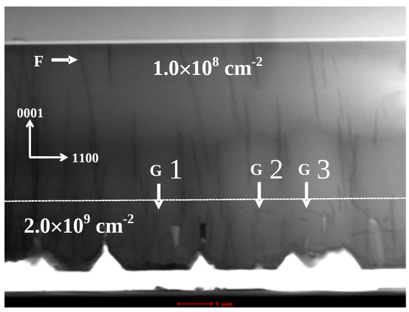

Fig. 2 TEM image of MELO-LED

The X-ray diffraction (XRD) rocking curves of these two samples are shown in Fig. 3. The linewidth for (102) planes was reduced from 552 to 472 arcseconds. The linewidth for (002) planes was only reduced from 338 to 335 arcseconds. The XRD linewidths for (102) and (002) planes are respectively related to edge and screw threading dislocation densities. The decrease in XRD linewidth indicates improved material quality. The improvement is attributed to the strain relaxation of the partially relieved GaN layer by interfacial etching and the subsequent regrowth. When the initial GaN epitaxial layer was grown on sapphire, a compressive strain was built up in the material due to the mismatched lattice constants and thermal expansion coefficients between GaN and sapphire. The KOH interfacial etching partially relieved GaN from sapphire interface and relaxed the compressive strain. This partially relieved layer served as a template for subsequent regrowth.

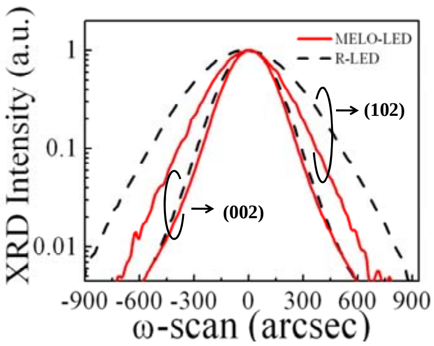

Fig. 3 X-ray diffraction rocking curves for MELO-LED and Reference-LED (R-LED) samples.

The light-current (L-I) and voltage-current (V-I) characteristics are shown in Fig. 4. The forward voltages of MELO-LED and R-LED are respectively 3.86 and 3.80 V at 20 mA and increase to 5.09 and 4.93 V at 100 mA. The electric characteristic of MELO-LED is still reasonably well maintained after chemical etching and regrowth process. The optical power was collected by an integrating sphere. The optical power of MELO-LED and R-LED are respectively 7.31 and 3.95 mW at 20 mA and 37.5 and 23.7 mW at 100 mA. Compared to R-LED, the MELO-LED output power exhibits 85% and 58% enhancement at 20 and 100 mA, respectively

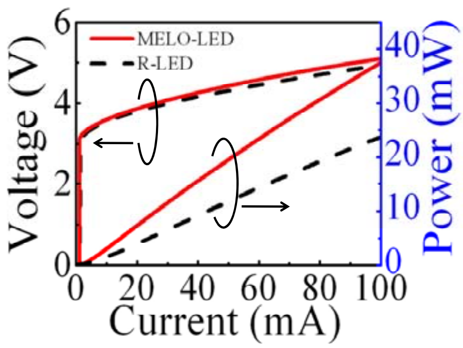

Fig. 4 L-I-V curves of IP-LED and R-LED

4. Conclusion

In summary, we have demonstrated multilayer epitaxial lateral overgrowth of GaN with anisotropically etched GaN/Sapphire interface structure for high efficiency light emitting diode. The density of threading dislocations can be efficiently reduced from 2.0×10^9 cm^{-2} to 1.0×10^8 cm^{-2} by multilayer epitaxial lateral overgrowth GaN on this structure. The reduction of dislocation was due to some bending and half loop of threading dislocations at the regrowth boundary. The overall optical output power has shown significant 85% enhancement at nominal operating current 20 mA, which is attributed to both improved crystal quality and better light extraction efficiency.

Acknowledgements

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