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High Quality Vertical LEDs Fabrication by Means of Mechanical Lift-off

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1. Introduction

Gallium nitride based material have recently attracted the whole world due to their potential applications in optoelectronic devices such as the light emitting diodes (LEDs), and the laser diodes [1-3]. These devices were grown heteroepitaxially onto foreign substrates like sapphire and SiC due to the shortage of high quality GaN substrates. The sapphire is the most commonly used substrate because of its relatively low cost, but it limits the devices performance due to its poor electrical and thermal conductivity. In the last decade, a laser lift-off (LLO) [4-5] and chemical lift-off [6] technique have been used to fabricate the freestanding GaN membrane for high performance optoelectric devices. However, the LLO may induce some effects at high temperature in the local area, releasing stress during the process. Here, we demonstrate the fabrication of mechanical lift-off high quality thin GaN with Hexagonal Inversed Pyramid (HIP) structure for vertical light emitting diodes (V-LEDs).

2. Experiments

First, we grew 3.5 μm GaN on sapphire as a template, and the GaN epilayer was etched in molten KOH for 10 mins at high temperature of 280 ^{o}C. The HIP GaN/air structure was formed by reversed etching from the N-face GaN. The etched paths with the threading dislocation propagation form the GaN top surface to the interface of GaN and sapphire. Second, the GaN based LED structures were grown on HIP GaN/air template in the lateral re-growth process. After Ni/Au p-GaN contact layer was deposited on the p-GaN layer in the E-gun process, which was followed by a 2 mins annealing process to achieve a low-resistance contact. The annealing temperature was 500 °C in ambient air. In the Au-Si wafer bonding process, the temperature of GaN thin film with HIP structure and sapphire substrate was under 400 °C. GaN thin film bears high-level thermal stress at the same time, and it will separate from sapphire substrate while cooling due to great difference of thermal expansive coefficient (CTE). This large CTE mismatch with GaN and sapphire supplies a big shear stress at interface and makes the HIP structure break off. Therefore, the sapphire substrate can be removed simultaneously with this mechanical lift-off technique and follows the process of vertical LED. The entire process of the flowchart and the thin GaN structure is shown in Fig. 1.

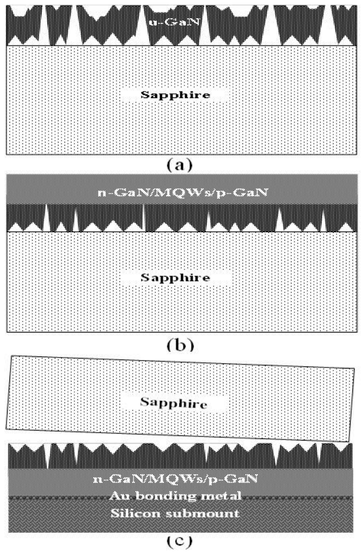

Fig. 1 The process of flowchart for fabrication of thin GaN structure : (a) The HIP GaN/air structure. (b) GaN based LED structure on HIP GaN/air template. (c) Remove sapphire substrate by mechanical lift-off during wafer bonding process.

3. Results and discussion

The cleaved sample which is tiled to be examined under scanning electron microscopy (SEM) after wet etching process is shown in Fig. 2(a). The HIP structure at GaN/sapphire interface can be clearly seen, and the V-shaped hexagonal pits were also formed on the surface. Fig. 2(b) shows the cross-sectional SEM image of the GaN based LED structure grown on HIP GaN/air template. It was found that the HIP structures were still complete and some air voids were also found in the HIP structures. This indicates that the vertical etched path was effectively terminated by means of the lateral overgrowth. Fig. 2(c) shows the Cross-sectional SEM image of the vertical LED structure after mechanical lift-off GaN LED/Silicon from sapphire substrate at high temperature during wafer bonding process. Fig. 2(d) shows the cross-sectional transmission electron microscopy (TEM) image of the re-growth

HIP GaN/air boundary. Most dislocations connect with each other by the bending and the loop formation without extending to the top surface.

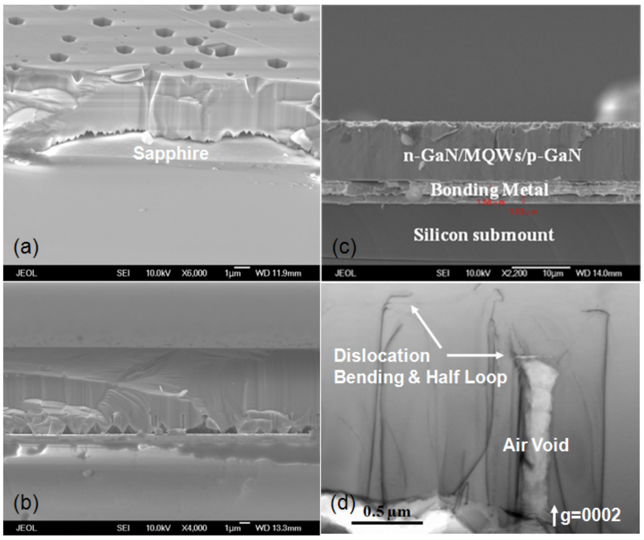

Fig. 2 Cross-sectional SEM images of (a) HIP structure formed in the wet etching process. (b) GaN based LED structure grown on HIP GaN/air template. (c) The vertical LED structure fabricated by mechanical lift-off; Cross-sectional TEM images of (d) The re-growth HIP GaN/air boundary. The diffraction condition is g=0002.

The strain of GaN growth on sapphire or Si substrate which is reduced by air gap structure had been discussed in the previous chapters [7-8]. The HIP structure partially relieves GaN from sapphire interface and thus relaxes the compressive strain. Table I shows the Raman shift of E_2 (high) mode and strain value for the unstrained GaN [9], the mechanical lift-off by HIP structure, the GaN epilayer re-growth on HIP structure and the GaN growth on sapphire. This partially relieved layer serves as a template in the subsequent re-growth process. It acts as a transition layer to partially filter the mismatched lattice constant and thermal expansion coefficient problems to improve the quality of the crystal. In other words, it implies that the residual stress of GaN based LED can as well be dramatically reduced while introducing the HIP structure to the GaN/sapphire interface.

Table I The Raman shift of E_2 (high) mode and strain value.

Sample	Unstrained GaN	Mechanical lift-off	Regrowth on HIP	GaN on Sapphire
E_2 ^{high} (cm^{-1})	566.5	567.11	567.82	569.5
Compressive Strain	0	6.03×10^{-4}	1.30×10^{-3}	2.96×10^{-3}

In order to compare the performance of V-LED fabricated by mechanical lift-off with regular LEDs on a sapphire substrate, regular LEDs were also fabricated by using the same LED structure for reference (Ref-LED) and the same size of 380×380 μm^2. The wavelength of the samples is located at near-UV range. Fig. 3 illustrates the light output intensity–current–voltage (L–I–V) characteristics under cw operation conditions for the V-LED and the Ref-LED. The forward voltage of V-LED and that of Ref-LED are 3.38 and 3.65 V, respectively. The light output of the V-LED is higher than the Ref-LED by 100% at 20 mA.

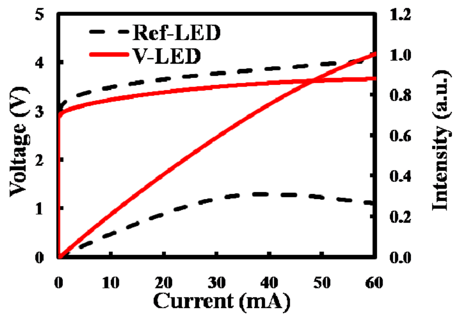

Fig. 3 L-I-V characteristics of the two fabricated LEDs.

4. Conclusion

In summary, we have successfully demonstrated the high quality thin-GaN vertical LED structure fabrication with the mechanical lift-off technique. The density of threading dislocations can be efficiently reduced about one order by re-growth GaN epilayer on the HIP structure. The reduction of dislocation was owing to the bending and the half loop of threading dislocations at the re-growth boundary. Raman spectroscopy analysis revealed that the compressive strain of GaN epilayer was effectively relaxed in the HIP structures and the inclination of TDs. Finally, the mechanical lift-off process was achieved by using the HIP structures as a sacrificial layer during wafer bonding process. The light output has shown significant 100% enhancement under operating current of 20 mA by applying this mechanical lift-off technique for fabrication the vertical LEDs.

Acknowledgements

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