High quality vertical light emitting diodes fabrication by mechanical lift-off technique

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Abstract

We report the fabrication of mechanical lift-off high quality thin GaN with Hexagonal Inversed Pyramid (HIP) structures for vertical light emitting diodes (V-LEDs). The HIP structures were formed at the GaN/sapphire substrate interface under high temperature during KOH wet etching process. The average threading dislocation density (TDD) was estimated by transmission electron microscopy (TEM) and found the reduction from 2×10^9 to 1×10^8 cm^{-2}. Raman spectroscopy analysis revealed that the compressive stress of GaN epilayer was effectively relieved in the thin-GaN LED with HIP structures. Finally, the mechanical lift-off process is claimed to be successful by using the HIP structures as a sacrificial layer during wafer bonding process.

1. Introduction

Gallium nitride based materials have recently attracted considerable attention all over the world due to their potential applications in the optoelectronic devices, such as light emitting diodes (LEDs) and laser diodes (LDs) [1-3]. These devices were usually grown heteroepitaxially onto foreign substrates such as sapphire and SiC. The sapphire is the most commonly used substrate because of its relative low cost, but it also limits the devices performance due to its poor electrical and thermal

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conductivity. During the last decade of years, the techniques of laser lift-off (LLO) [4,5] and chemical lift-off (CLO) which use CrN layer [6], ZnO layer [7], and Si-doped n-GaN layer [8] as the sacrificial layer have been adopted to fabricate the freestanding GaN membrane and the vertical LEDs for the purpose of high performance optoelectronic devices. However, the LLO process may induce some possible damages under high temperature in the GaN/sapphire interface. And even though the CLO can prevent the GaN layer from the laser damage during the laser lift-off process, but it also makes another chemical etching damages and reduce the crystal quality.

In this work, we announce the fabrication of high quality thin-GaN with hexagonal inversed pyramid (HIP) structures by mechanical lift-off (MLO). The interface morphologies and the optical properties of lifted-off GaN epilayer will be analyzed.

2. Experiments

The GaN-based epilayer and LED structure was used in this study were all prepared by metal–organic chemical vapor deposition (MOCVD). We first deposited a 3 μm-thick un-doped GaN on a c-plane sapphire substrate as a template. The GaN epilayer was observed to be etched in the molten KOH for 10 mins at high temperature of 280 ^{o}C. The Hexagonal Inversed Pyramid (HIP) GaN/air structure was formed by the reversed etching from the N-face GaN. The etched path along with the threading dislocation propagation form the GaN top surface to the interface of GaN and sapphire, and the related processes have been presented in our previous study [9].

Next, the GaN-based LED structures were grown on HIP GaN/air template in the lateral re-growth process. The LED device structure was 2 μm un-doped GaN, 3.5 μm n-doped GaN, ten pairs of $Al_{0.02}Ga_{0.98}N/In_{0.1}Ga_{0.9}N$ quantum wells 13/2.5 nm, and 100 nm of p-doped GaN cap layer. The designed emission wavelength is measured at approximately 405 nm. 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 accomplish a low-resistance contact. The annealing temperature was 500 °C in ambient air. After annealing process, a reflective layer of 1500 Å Al was deposited to prevent light from reaching the absorbing Si substrate. In this way, a metalized Ni/Au bonding layer was deposited on the top of the Al layer. The thicknesses of Ni and that of Au layer were 1500 and 2000 Å, respectively. This 1500 Å Ni layer serves as an adhesive barrier layer while the 2000 Å Au layer serves as the seed layer in the electroplating process of 2 μm thick Au layer which is used to do Au-Si wafer bonding.

In the Au-Si wafer bonding process, GaN thin film with HIP structure and sapphire substrate were under 400 °C. GaN thin film will carry high-level thermal stress under this condition, and it will separate from sapphire substrate during cooling process because of different thermal expansive coefficient (CTE). This prominent CTE mismatch with GaN and sapphire brings an unbearable shear stress to the interface and as well makes the HIP structure break off. Therefore, the sapphire substrate can be removed simultaneously by way of this mechanical lift-off technique and follows the process of vertical-LED (V-LED). The entire process of flowchart and thin GaN structure is shown in Fig. 1.

3. Results and discussion

The cleaved sample, which is titled to be examined under the scanning electron microscopy (SEM) after wet etching process, is shown in Fig. 2(a), where the HIP structure at GaN/sapphire interface can be clearly observed and the V-shaped hexagonal pits of about 2×10^{7} cm^{-2} were also formed on the surface. Additional GaN was grown on the etched GaN wafer to fill up both the etched openings and surface pits to provide a flat top surface for the subsequent LED device growth. Fig. 2(b) reveals the cross-sectional SEM image of the GaN-based LED sample at the GaN/sapphire interface in the re-growth process. It was discovered that the HIP structures were still complete and some air voids were also found in the HIP structures. This result indicates that the vertical etched path was effectively hindered by means of the lateral overgrowth. Fig. 2(c) illustrates the cross-sectional transmission electron microscopy (TEM) image of the GaN-based LED sample with the white lines indicating the re-growth boundary of the GaN epilayer regions. The formation of air void usually observed in the etching boundary during the lateral re-growth process. The dislocation density at the bottom of the GaN layer is rendered at about 2×10^{9} cm^{-2} and slightly reduces to 1×10^{8} cm^{-2} at the top of the GaN layer. The density of dislocations degrades due to bending and a half loop of threading dislocations at the re-growth boundary. Most dislocations associate with each other by bending and loop formation, and they do not extend to the top surface as we can observe in Fig. 2(d).

Fig. 3(a) unveils the Cross-sectional SEM image of the vertical LED structure after mechanical lift-off GaN LED/Silicon from the sapphire substrate at high temperature in the wafer bonding process. The inset in Fig. 3(a) reveals a top-view SEM image of the HIP surface morphology. Obviously, the cone shape structure and etched path were formed on the GaN surface in this sample. The size and density of etch cone shape estimated from SEM were 0.5 μm ~ 1 μm and 8×10^{7} /cm^{2}, respectively. Accordingly, the etched paths were created throughout the GaN/sapphire interface and the GaN epilayer which is partially attached to the sapphire substrate. Therefore, the mechanical lift-off process was proved to be available by regarding the HIP structures as a sacrificial layer at high temperature during the wafer bonding process. Fig. 3 (b) shows the room temperature Raman spectrum of the GaN epilayer re-growth on HIP structure and mechanical lift-off by HIP structure. The Raman shift peak of E_2 (high) for the GaN epilayer re-growth on HIP structure and mechanical lift-off by HIP structure were located at around 567.82 and 567.11 cm^{-1}, respectively. We can obtain the strain value of GaN epilayer with the following equation (1) [10].

$$\Delta\omega = \omega_{E_2} - \omega_0 = C\cdot\sigma_{xx}$$

$$\sigma_{xx} = M_f\cdot\varepsilon_{xx}$$

(1)

$$\varepsilon_{xx} = \frac{\Delta\omega}{C\cdot M_f}$$

As the equation uncovers, $\Delta\omega$ is the Raman shift peak difference between the strained GaN epilayer ω_{E2} and the unstrained GaN epilayer ω_0 (566.5 cm^{-1}). C is the biaxial strain coefficient, which is 2.25 cm^{-1}/GPa. M_f is the biaxial modulus to the substrate, which is 449.6 GPa [11]. σ_{xx} is the biaxial stress, and ε_{xx} is the biaxial strain. The calculated in-plane compressive strain ε_{xx} are approximately 1.30×10^{-3} and 6.03×10^{-4} for the GaN epilayer re-growth on HIP structure and mechanical lift-off by HIP structure, respectively. The Raman shift peak of E_2 (high) for GaN on sapphire without HIP structure is 569.5 (cm^{-1}), and the in-plane compressive strain ε_{xx} is about 2.97×10^{-3}. In other words, it implies that the residual stress of GaN-based LED can also be considerably declined while introducing the HIP structure to the GaN/sapphire interface. 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 applying the same LED structure for reference (Ref-LED) and the same size of 380×380 μm^{2}. The electroluminescence (EL) spectra of both LEDs collected in the normal to the front surface direction at 20 mA is shown in Fig. 4 (a). The peak wavelength of V-LED and that of

Ref-LED are 405 and 406nm, respectively. The inset in Fig. 4 (a) shows the variation of LED emission peak wavelength of the V-LED and that of the Ref-LED under high current continuous-wave (cw) operation conditions. The peak wavelength of the Ref-LED showed a relatively larger redshift of about 16 nm from a low current of 20 mA to a high current of 100 mA. However, the peak wavelength of theV-LED displayed only a slight redshift of about 5 nm in the same current range, indicating the relief of compressive strain in V-LED. Fig. 4 (b) shows the light output power–current–voltage ($L - I - V$) characteristics under cw operation conditions for the V-LED and the Ref-LEDs. The forward voltage of V-LED and that of Ref-LED are 3.38 and 3.65 V, respectively. The light output power of the V-LED is higher by 100% than the Ref-LED at 20 mA.

The strain of GaN growth on sapphire or Si substrate to be reduced by air gap structure had been discussed [12,13]. The HIP structure partially relieves GaN from sapphire interface so that relieves the compressive strain. This partially relieved layer serves as a template in the subsequent re-growth process. It acted as a transition layer to partially filter the mismatched lattice constant and thermal expansion coefficient problems to improve the crystal quality. Therefore, we speculate that this HIP structure will efficiently reduce the stress state on re-growth GaN epilayer, in which the high efficiency vertical LED was demonstrated.

4. Conclusion

In summary, we have successfully demonstrated the fabrication of mechanical lift-off high quality thin GaN LED with HIP structures as a sacrificial layer during wafer bonding process for vertical LEDs. The density of threading dislocations can be efficiently reduced from 2×10^9 to 1×10^8 cm^{-2} by applying the re-growth GaN epilayer on HIP structure. The reduction of dislocation was due to bending and a half loop of threading dislocations at the re-growth boundary. The in-plane compressive strain ε_{xx} are calculated to be about 1.30×10^{-3} and 6.03×10^{-4} for the GaN epilayer re-growth on HIP structure and mechanical lift-off by HIP structure, respectively. It implies that the residual stress of GaN-based LED can also be greatly reduced while introducing the HIP structure to the GaN/sapphire interface. The peak wavelength of the V-LED also shows only a slight redshift of about 5 nm in the spectrum from 20 mA to 100 mA. The result indicates the relief of compressive strain in V-LED. Finally, the overall optical output power has shown significant 100% enhancement under operating current 20 mA with this mechanical lift-off technique for fabrication the vertical-LED.

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Figure caption

Fig. 1. The process 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.

Fig.2 Cross-sectional SEM images of (a) HIP structure formed in the wet etching process (b) The re-growth HIP GaN/air interface; Cross-sectional TEM images of (c) GaN-based LED structure grown on HIP GaN/air template (d) The re-growth HIP GaN/air boundary. The diffraction condition is g0002.

Fig.3 (a) Cross-sectional SEM image of the vertical LED structure after mechanical lift-off GaN LED/Silicon from sapphire substrate. (b) Room temperature Raman spectrum of GaN epilayer re-growth on HIP structure and mechanical lift-off by HIP structure. Inset in Fig. 3(a) shows top-view SEM image of the HIP surface morphology.

Fig. 4. (a) EL spectra of Ref-LED and V-LED in normal direction at 20mA. (b) L-I-V characteristics of the two fabricated LEDs. Inset in Fig. 4(a) shows peak wavelength shift of the LEDs.

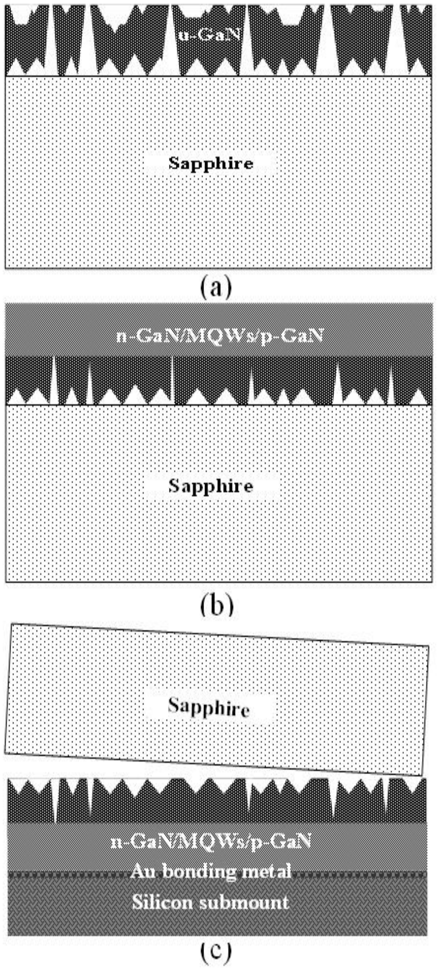

u-GaN
Sapphire
(a)
n-GaN/MQWs/p-GaN
Sapphire
(b)
Sapphire
n-GaN/MQWs/p-GaN
Au bonding metal
Silicon submount
(c)

Fig. 1.

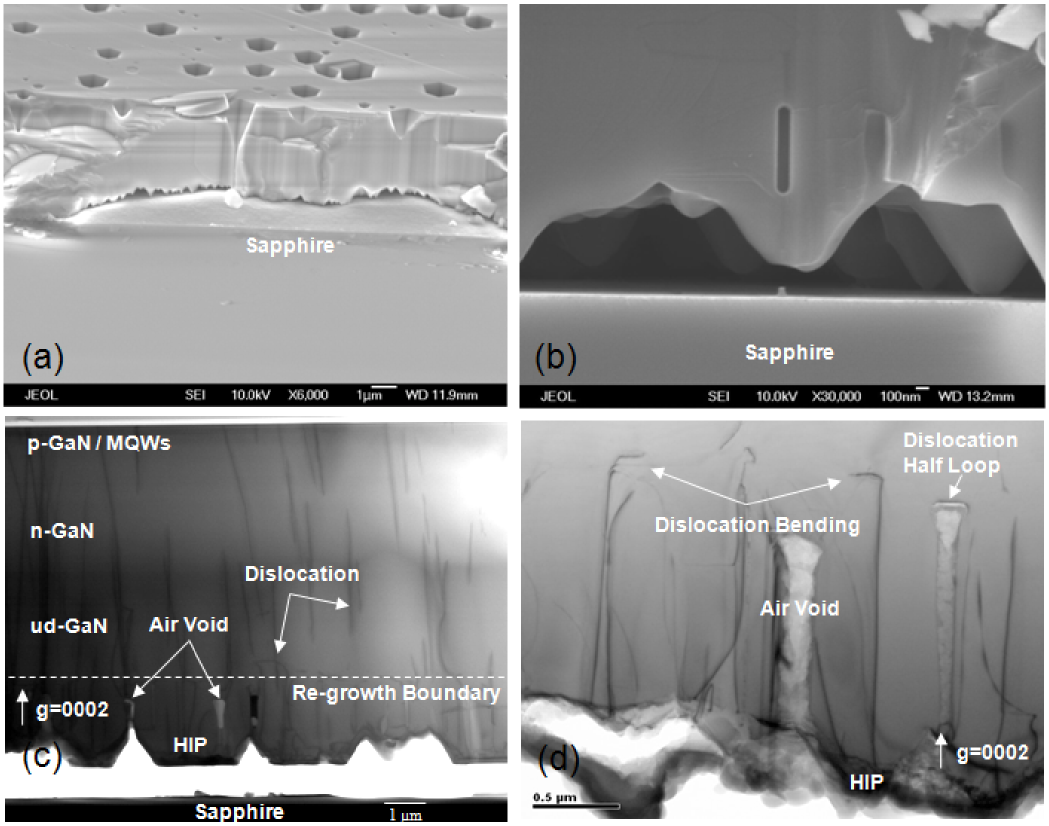
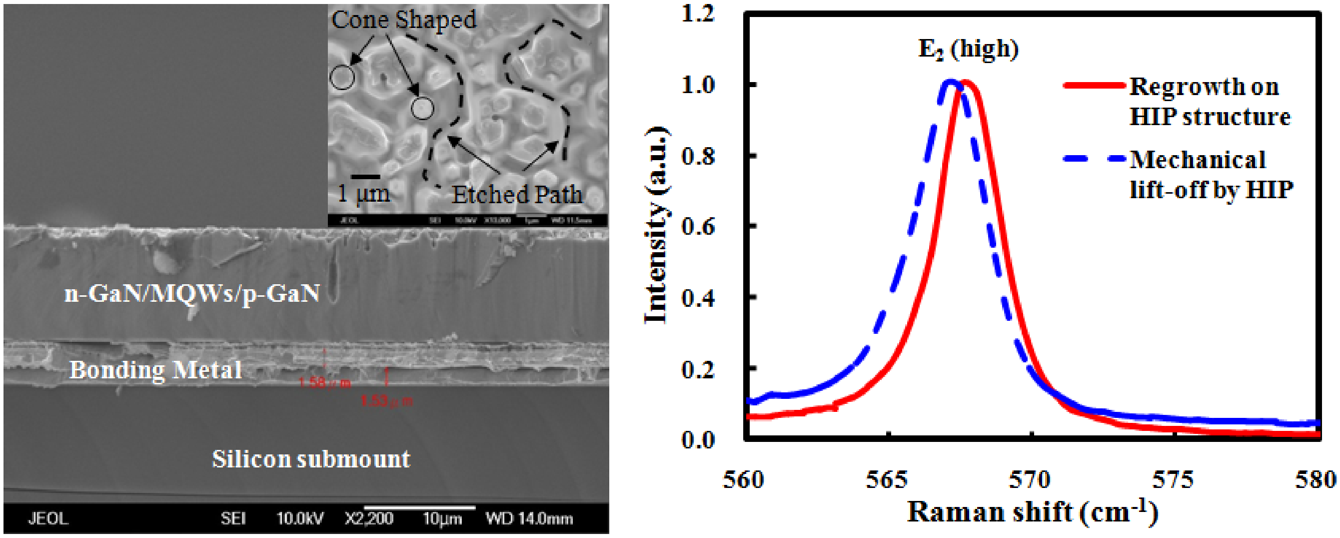
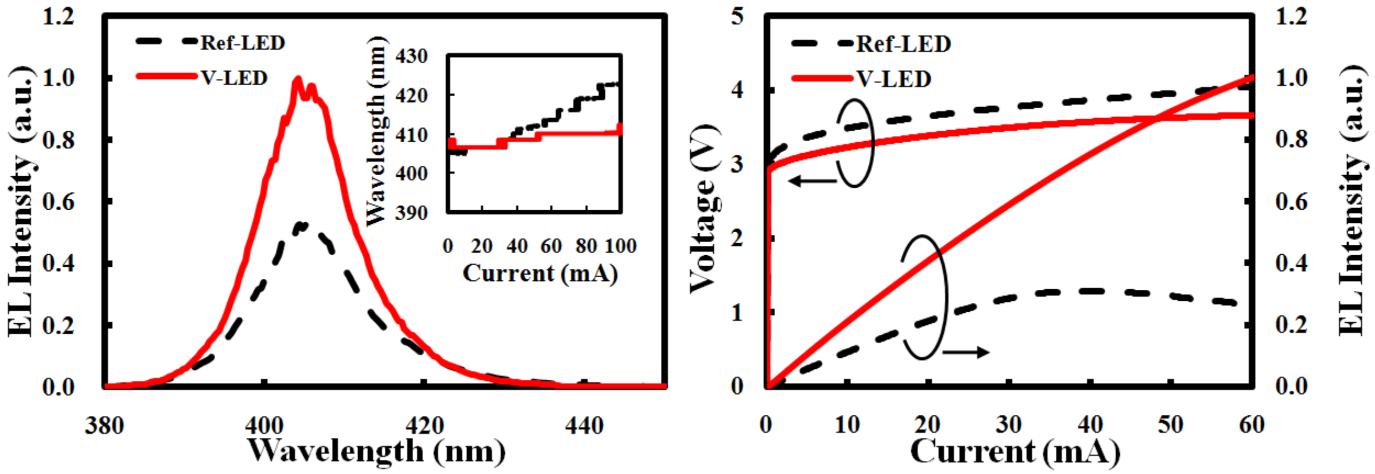

Sapphire
(a)
JEOL SEI 10.0kV X6,000 1μm WD 11.9mm
Sapphire
(b)
JEOL SEI 10.0kV X30,000 100nm WD 13.2mm
p-GaN / MQWs
n-GaN
Dislocation
ud-GaN
Air Void
Re-growth Boundary
g=0002
HIP
(c)
Sapphire
1 μm
Dislocation Half Loop
Dislocation Bending
Air Void
g=0002
HIP
(d)
0.5 μm

Fig. 2.


Cone Shaped
1 µm
Etched Path
JEOL SEI 10.0kV X13,000 1µm WD 11.5mm
n-GaN/MQWs/p-GaN
Bonding Metal
1.58 µm
1.53 µm
Silicon submount
JEOL SEI 10.0kV X2,200 10µm WD 14.0mm
E2 (high)
Regrowth on HIP structure
Mechanical lift-off by HIP
Intensity (a.u.)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
560
565
570
575
580
Raman shift (cm-1)

(a) (b)

Fig. 3.


1.2
1.0
0.8
0.6
0.4
0.2
0.0
EL Intensity (a.u.)
Ref-LED
V-LED
380
400
420
440
Wavelength (nm)
430
420
410
400
390
Wavelength (nm)
0
20
40
60
80
100
Current (mA)
5
4
3
2
1
0
Voltage (V)
Ref-LED
V-LED
0
10
20
30
40
50
60
Current (mA)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
EL Intensity (a.u.)

(a)

(b)

Fig. 4.