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An Investigation of GaN-Based LED with MBE Grown Nanopillars by MOCVD

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1. Introduction

Recently, GaN-based epilayer, with superior properties in comparison with other III-V compound semiconductors, plays a key role in a wide range of optoelectronic applications such as light-emitting diodes (LEDs) and laser diodes with the luminescence spectra covering an energy range from infrared to ultraviolet. Unfortunately, the lack of suitable substrate limits the full development of superiorities of InGaN-based devices. Most GaN-based epilayer was grown on sapphire substrate by heteroepitaxial techniques, such as metal-organic chemical vapor deposition (MOCVD) [1]. GaN-based epilayer contains high threading dislocation densities (TDDs) presently (around 10^8~10^{10} cm^{-2}) due to the large lattice mismatch and thermal expansion coefficients difference [2].

To acquire high crystalline quality GaN-based epilayer on sapphire substrate, a lot of studies focusing on ultra-flat surface, low TDDs were demonstrated, such as epitaxial lateral overgrowth (ELOG) [3], defect selective passivation [4], microscale SiO_x patterned mask [5], and patterned sapphire substrate (PSS) [6]. Some groups demonstrated recently that low strain and TDDs were achieved when applying GaN nano-columns to GaN-based epilayer grown by MOCVD or hydride vapor phase epitaxy (HVPE) [7,8]. Those nano-structures were achieved by molecular beam epitaxy (MBE) and mainly focused on the epitaxial growth of GaN epilayer rather than LEDs devices properties.

In this work, the producing of high quality and low defect density GaN-based LED via introducing GaN nanopillars (NPs) as template layer was achieved. Furthermore, the residual stress of the sample was characterized by room temperature Raman spectroscopy and the dislocation distribution were invested by transmission electron microscopy (TEM). The comparison of devices properties between conventional and NPs-template LEDs was revealed by room temperature current-voltage (I-V) and light-current (L-I) characteristics.

2. Experiments

The growth of the GaN-based LED overgrowth on NPs structure was carried out by combining RF-MBE (ULVAC MBE) and MOCVD (VEECO D75) system. The epitaxial structure of the GaN-based LED overgrowth on NPs is depicted in Fig. 1 First, the self-assembled GaN NPs structure was grown on sapphire substrate by RF-MBE, and the related processes have been presented in our previous study [9]. In Fig. 1(a), the mean diameter of straight GaN NPs is about 100nm with a gap space less than 5nm, which are grown on 25nm AlN buffer layer with 0.5μm height by RF-MBE. Next, the GaN epilayer and GaN-based LED were fabricated upon GaN NPs by a low pressure MOCVD system. Fig. 1(b) shows the overgrowth structure of GaN-based LED, comprising a 30nm GaN nucleation layer (GaN NL), a 1μm undoped GaN (u-GaN), a 3μm n-doped GaN (n-GaN), a 10pairs InGaN/GaN multiple quantum wells (MQWs), and a 0.4μm p-doped GaN (p-GaN) cap layer. Besides, the growth of GaN-based LED on sapphire without GaN NPs was also prepared for comparisons. The LED sample in the study had a chip size of 350μm× 350μm, fabricated using standard photolithography and dry etching techniques.

3. Results and discussion

Table I shows the room temperature Raman shift peak of E_2^{high} for GaN epilayer grown on sapphire with and without GaN NPs. The spectrum contains two Raman shift peaks: E_2^{high} mode of GaN epilayer and another is A_1^{LO} mode. The Raman shift peak of E_2^{high} for GaN epilayer grown on sapphire with and without GaN NPs was located at 567.5 and 569.5 cm^{-1}, respectively. The corresponding stress and strain value of GaN epilayer is calculated using the following equation (1) [10, 11]:

$$\Delta\omega_\lambda = \omega_\lambda - \omega_0 = 2a_\lambda\varepsilon_{xx} + b_\lambda\varepsilon_{zz} = 2\left(a_\lambda - \frac{C_{13}}{C_{33}}b_\lambda\right)\cdot\frac{\sigma_{xx}}{M_f} = C\sigma_{xx} \qquad (1)$$

where $\Delta\omega_\lambda$ is Raman shift peak difference between the strained GaN epilayer ω_λ and the unstrained GaN epilayer ω_0 (566.5 cm^{-1}); C is biaxial strain coefficient, which is 2.48 cm^{-1}/GPa. The value of in-plane compressive stress σ is about 0.402 GPa and 1.208 GPa for GaN epilayer grown on sapphire with and without GaN NPs, respectively. It implies evidently that the residual stress of GaN-based LED can be greatly reduced while introducing GaN NPs at LED-sapphire interface, as shown in the Fig. 1. Therefore the structure of GaN NPs inserting at sapphire/GaN interface can effectively reduce the level of strain in the GaN-based LED while the conventional one contains a high-level strain.

Cross-sectional TEM image (with reciprocal lattice vector g=0002) of u-GaN grown on GaN NPs was represented in Fig. 2. There are voids existing in the middle region of u-GaN clearly and which resulted in threading dislocation bending toward these voids. This dislocation-gathering mechanism leads to great reduction of dislocation density and enhancement of crystal quality. Besides, the voids serve the light diffraction well, *i.e.* effectively diffracting the light into the escape-cone and increasing the escape probability. The formation of voids in u-GaN, additionally, plays an important role in in-plane stress relaxation for achievement of high quality GaN LED..

Fig. 3 shows the light output of the LED devices with and without GaN-NPs as a function of injection current. Applying a 20mA forward injection current to these devices, the sample with GaN NPs performs higher light intensity than that without GaN NPs by ~2 times. Such a significant enhancement in electroluminescence intensity is resulted from the realization of GaN epilayer on sapphire with GaN NPs, which leading to TDDs reduction and achieving a high-quality GaN-based LED ultimately. Furthermore, the efficiency droop of GaN-based LED device can be improved as the GaN NPs were introduced as well. The inset of Fig. 3 displays the current-voltage (I-V) characteristics of these devices with and without GaN-NPs structure at room temperature. The corresponding forward voltage at 20mA was 3.4 and 3.8V, respectively. It reveals that the sample with GaN-NPs has a smaller driving voltage. Referring back to Fig. 2, the defects were suppressed effectively when the GaN NPs were introduced. Thus, the leakage path induced by defect is found to be dramatically suppressed.

4. Conclusions

High quality GaN-based LED was fabricated successfully by MOCVD using MBE GaN NPs template. Room temperature Raman shift peak of E_2^{high} demonstrated great reduction in the strain of sample with GaN NPs. Cross-sectional TEM image revealed the quality enhancement mechanism, i.e. void-induced dislocation-gathering and stress-relaxation clearly. Additionally, the LED devices fabricated on sapphire with GaN NPs have light output ~2 times higher than that of conventional one at 20mA.

Ultimately, MOCVD-grown LED on GaN NPs suggests an effective technique to light output enhancement and strain reduction. Further improvement of GaN LED can be realized by optimizing the nanopillars, such as shape, dimension, periodicity arrangement, and crystalline quality and so on.

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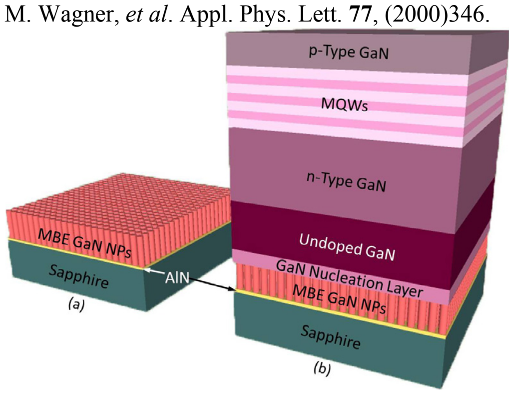

Fig. 1 Schematic of (a) GaN nanopillars template on sapphire with AlN buffer layer. (b) GaN-based LED structure on GaN-NPs template on sapphire.

Table I Room temperature Raman shift peak of E_2^{high} for GaN epilayer grown on sapphire with and without GaN NPs. The related stress and strain are showed simultaneously.

Sample	GaN on NPs	GaN on Sapphire
E2high(cm-1)	567.5	569.5
Compressive Stress σ_{xx}(GPa)	0.402	1.208
Compressive Strain ε_{xx}(%)	0.090	0.269

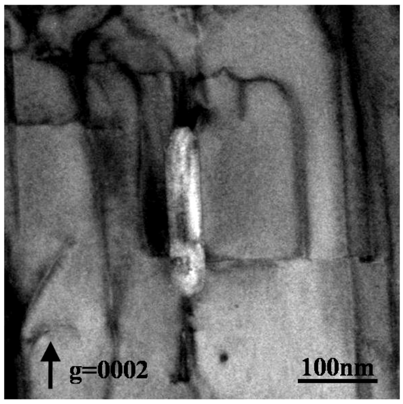

Fig. 2 Cross-sectional TEM image of u-GaN region on NPs. The void-induced dislocation bending and gathering are represented here. The reciprocal lattice vector is g=0002.

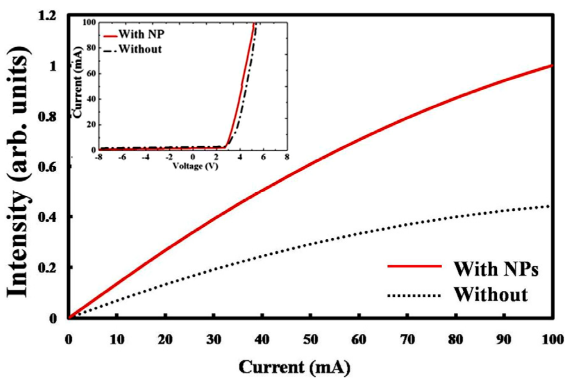

Fig. 3 The light output vs. forward current of GaN-based LED on sapphire with and without GaN NPs. Inset figure shows current-voltage (I-V) characteristics of samples.