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InGaN multiple quantum wells grown on ELO GaN templates and the optical properties characterization

Hailong Zhou[a], S.J. Chua[b,*], Keyan Zang[b], L.S. Wang[b], S. Tripathy[b], N. Yakovlev[b], Osipowicz Thomas[a]

[a]Department of Physics, Faculty of Science, 2Science Drive 3, 117542 Singapore, Singapore
[b]Institute of Materials Research & Engineering, 3 Research Link, 117602, Singapore, Singapore

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Abstract

Epitaxial lateral overgrowth of gallium nitride with $(1\,1\,\bar{2}\,2)$ facets was realized by metal organic chemical vapor deposition on GaN/sapphire (0 0 0 1) substrates with SiO_2 stripe mask. After wet etching of the mask, periodic multiple quantum wells (MQWs) InGaN/GaN structures were grown on the whole surface. Cross-sectional transmission electron microscopy (TEM) showed that a higher growth rate on (0 0 0 1) plane compared to $(1\,1\,\bar{2}\,2)$ facet. The well thickness and In composition of the quantum wells (QWs) were analyzed by the cross-sectional and high resolution X-ray diffraction (HR-XRD) measurements. Micro photoluminescence spectra confirmed that the ELO InGaN/GaN MQWs structures on the $(1\,1\,\bar{2}\,2)$ plane provide nearly multi-wavelengths output light. This is suitable for display devices based on the white color optical system.

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1. Introduction

The successful commercialization of blue-green light emitting diodes (LEDs) and blue laser diodes (LDs) has led to much interest in group-III nitrides semiconductors. Gallium nitride (GaN) has a large direct band gap of 3.42 eV [1] at room temperature, which makes it useful in short wavelength lasers [2] and visible LEDs [3]. Their common part is a layer with multiple quantum wells (MQWs) to trap electrons and holes for their efficient recombination. The performance of these LEDs and LDs can be improved, if their design overcomes two main issues: (1) There is high dislocation density 10^9–$10^{10}\,cm^{-2}$ in GaN grown on traditional sapphire substrates because of large lattice mismatch (~14%). Possible ways are to use better matching substrates like SiC or GaN [3], which are usually more expensive, or to grow GaN using epitaxial lateral overgrowth (ELO) technique. In the latter case, a mask of a foreign material usually SiO_2 or SiN_x is deposited on GaN seed layer and the growth is resumed on the openings of the mask. Thus GaN growing laterally over the mask has lower dislocation density than the seed layer. (2) When GaN growth surface is (0 0 0 1) plane, planar strain induced by the different lattice constants of the GaN quantum wells (QWs) and the AlGaN barrier layers gives rise to strong internal piezoelectric fields [4]. This leads to local separation of electrons and holes in these QWs, poor overlap of electron and hole wave functions, long radiative lifetimes [5] and low internal quantum efficiencies [6–8], where competing non-radiative channels are always present in the device structures. Reduction of electrostatic fields is possible by growing the structures on non-polar or semi-polar plane of sapphire, e.g. on *r*-plane, where GaN grows in $(1\,1\,\bar{2}\,2)$ direction [9,10]. Other approaches make use of more exotic substrates such as $LiAlO_2$ [11], on which pure *m*-plane GaN $(1\,\bar{1}\,0\,0)$ growth was achieved. However, on these substrates, it is difficult to achieve high crystalline

*Corresponding author. Fax: +65 69820785.
E-mail address: elecsj@nus.edu.sg (S.J. Chua).

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quality of GaN, and device performance cannot compete with that obtained on the commonly used *c*-plane of sapphire.

A so-called facet-controlled epitaxial lateral overgrowth (FACELO) technique can help to overcome both problems. It is realized by starting the epitaxial growth on (0 0 0 1) plane and tuning the growth conditions to develop other facets, e.g. $(1\,\bar{1}\,0\,1)$ and $(1\,1\,\bar{2}\,2)$, on ELO stripes [12]. FACELO GaN was used as a substrate to grow InGaN/GaN MQWs with reduced piezoelectric field [13,14].

In this work, InGaN/GaN MQWs on FACELO GaN $(1\,1\,\bar{2}\,2)$ facets were grown by the metal organic vapor phase epitaxy (MOVPE). Scanning electron microscopy (SEM) and cross-sectional transmission electron microscopy (TEM) were used to characterize the morphology and structure of MQWs. Concentration of Indium was measured using HR-XRD. Optical properties of MQWs on individual $(1\,1\,\bar{2}\,2)$ facets were studied using micro-photoluminescence (PL) spectroscopy. Since the emission efficiency does not show a noticeable emission wavelength dependence, this type of structure has potential as light-emitting devices with multi-wavelengths that perform numerous color controllability such as pastel and white colors.

2. Experimental procedure

A 2.0 μm thick GaN layer was first deposited on a *c*-plane sapphire substrate by MOVPE. Trimethyl-metals and ammonia (NH_3) were, respectively, used as precursors for group III, N, and H_2 was used as carrier gas. About 100 nm thick SiO_2 mask was patterned into stripes oriented in the $(1\,\bar{1}\,0\,0)$ direction of GaN, defining a 4 μm wide opening with a period of 12 μm. After 30 min of regrowth on these templates, ELO GaN with $(1\,1\,\bar{2}\,2)$ facets were selectively overgrown. The growth temperature was 950 °C and reactor pressure was 500 Torr. After the SiO_2 mask was removed by HF solution, five periods of InGaN/GaN MQWs were grown on the whole surface. The target In composition in the wells was 40%. The growth temperature was about 760 °C, the reactor pressure was kept at 80 Torr, the growth time of well and barriers was 0.4 and 1.2 min, respectively.

The morphology of the layers and cross-sections were studied with a JEOL 6700 FE SEM. The internal structure of the MQWs was studied by Philips CM300 FEG TEM. HR-XRD was also performed on the *c*-plane reference MQW sample using a high resolution Philips MRD system. The PL spectra were recorded at room temperature using a 325 nm excitation line with a lateral resolution of 2 μm (Renishaw 2000 set up).

3. Results and discussion

The morphology of ELO InGaN/GaN MQWs has the shape of a prism with triangle in the cross-section, as seen on SEM image, (Fig. 1). The triangles are 7 μm high and 8.8 μm wide. Fig. 2 shows the cross-sectional TEM images of the InGaN/GaN MQWs grown simultaneously on the $(1\,1\,\bar{2}\,2)$ facets and on the *c*-planes. From Fig. 2(a), it is clearly seen that the five periods of InGaN/GaN MQWs are grown on the $(1\,1\,\bar{2}\,2)$ facet successfully with total thickness of approximately 10 nm. From Fig. 2(b), we observed *c*-plane or (0 0 0 1)-oriented MQWs with total thickness 60 nm. There are evidently different growth rates of MQWs on these facets. As the GaN growth rates are found to be 6 times higher along the *c*-direction, the well and barrier width in these planes are larger than those on the $(1\,1\,\bar{2}\,2)$ facets. The well to barrier ratio was determined by growth time. The well and barrier thickness are approximately 1 and 1 nm, respectively, on $(1\,1\,\bar{2}\,2)$ facets and about 6 and 6 nm, respectively, on *c*-plane. The growth rate on the two facets is controlled by the growth temperature and pressure. With the same growth pressure, lower growth temperature will lead to higher *c*-direction growth rate and lower lateral growth rate; these observations are quite similar to those in Ref. [12] (Fig. 3).

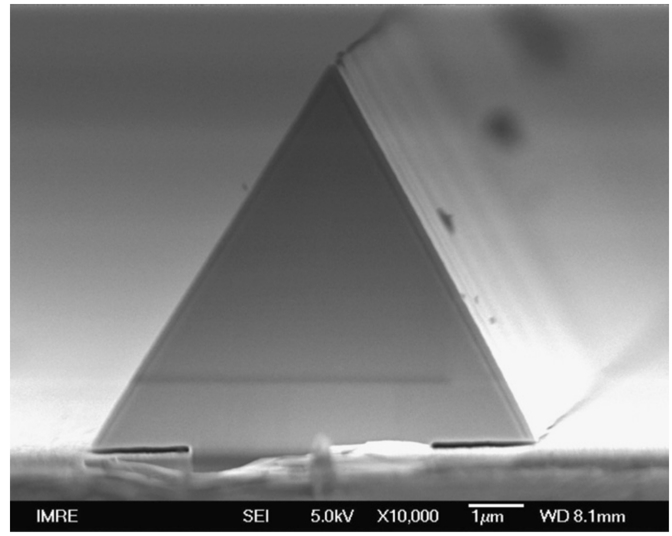

Fig. 1. Cross-sectional SEM of the ELO InGaN/GaN MQWs on the GaN/sapphire template.

To determine the In composition in the InGaN/GaN MQWs, the XRD profile of the *c*-plane InGaN/GaN MQWs was taken in the vicinity of the (0 0 0 2) diffraction. Satellite peaks were clearly seen, and the In compositions, well and barrier thicknesses were estimated to be 40.2%, 3.8, and 4.9 nm, respectively, by a fit using the dynamical diffraction theory. The error seems very small because a 1% difference in the In composition caused a discernible difference between the simulated and the experimentally obtained XRD profiles. It also can be said that the thickness determined by the XRD is more reliable than TEM.

Fig. 4 shows a PL spectrum acquired at room temperature. The PL peaked at 563 nm (2.2 eV), and covered wavelengths from 430 to 800 nm, which corresponds to almost the entire visible range. The estimated

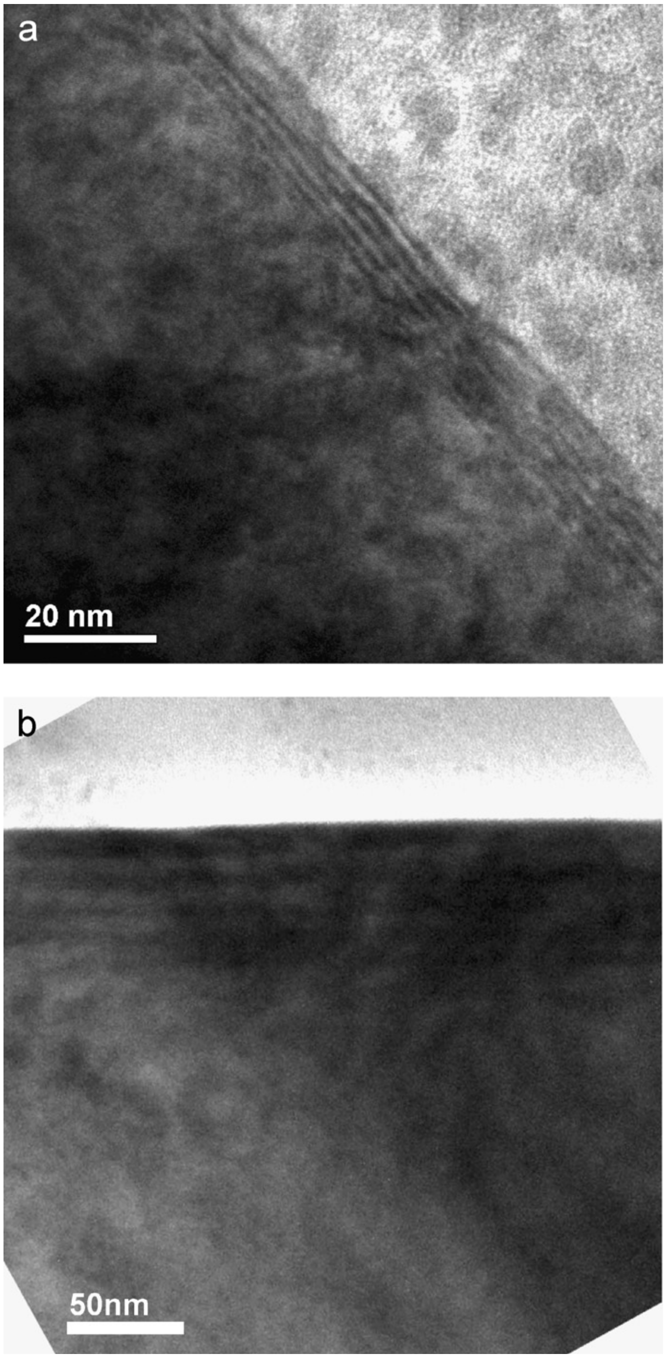

Fig. 2. The cross-sectional TEM images of the ELO InGaN/GaN MQWs, (a) taken along the $(1\,1\,\bar{2}\,2)$ faceted MQWs; (b) taken along the c-plane MQWs.

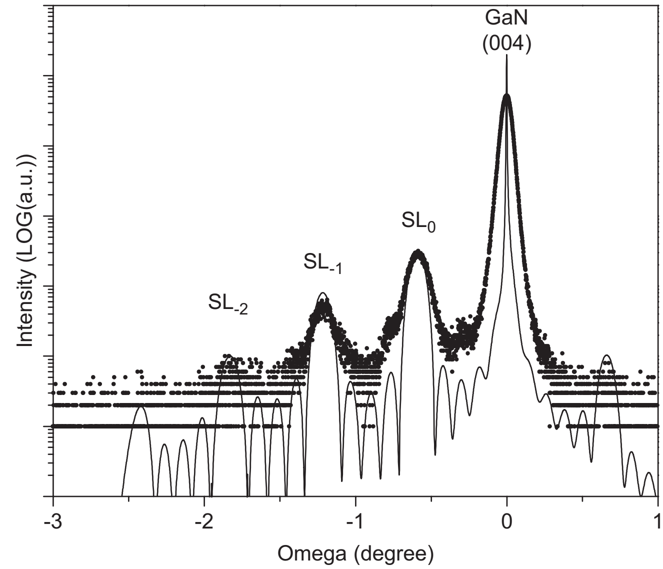

Fig. 3. High-resolution X-ray diffraction $\omega/2\theta$ experimental (• • •) and calculated (——) triple axis symmetrical scans near the (0 0 0 4) GaN diffraction peak was taken on the reference c-plane InGaN/GaN MQWs.

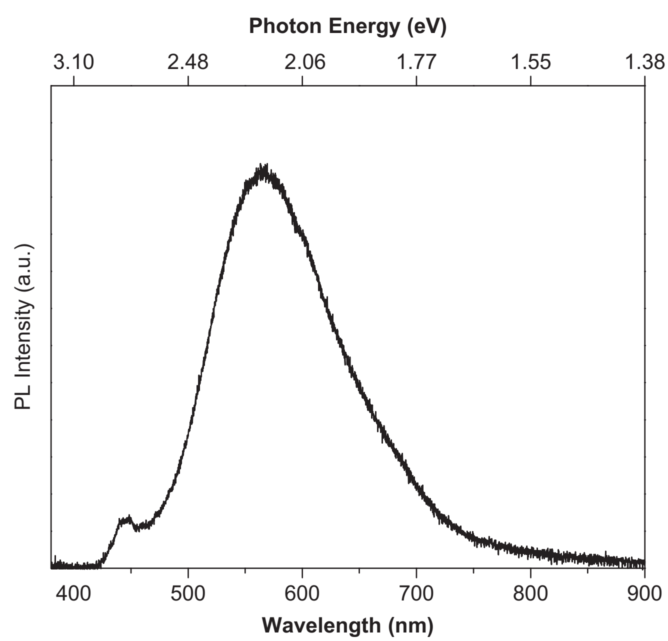

Fig. 4. Room temperature micro-PL spectra recorded from the $(1\,1\,\bar{2}\,2)$ facets ELO AlGaN/GaN MQWs.

FWHM was (459 MeV), which is more than twice as large as a typical value for conventional c-oriented InGaN/GaN MQWs; these observations are quite similar to those in Ref. [14]. This anomalously broad emission was due to the In spatial distribution and characterized the luminescence color of the present $(1\,1\,\bar{2}\,2)$ MQWs. It is classified into whitish emerald green, far from monochromatic light. Since the In distribution in a plane is controlled by the growth conditions, various apparent colors including white can be realized using only the structure proposed in this study. This will be different from conventional technologies where the light color is designed by, for example, using several emitters with different output colors or using phosphors as a color converter. It is also noteworthy that some theoretical studies have indicated that InGaN/GaN QWs with a crystalline tilt should have weaker internal electric fields and consequently, higher emission efficiency [8,15]. Our MQWs were directed toward $(1\,1\,\bar{2}\,2)$ tilted 56° from the (0 0 0 1) direction. Thus, a high internal efficiency was expected. Although the maximum internal quantum efficiency achieved in the red spectral range by InGaN MQWs based LEDs thus far is a few percent, a red component in our $(1\,1\,\bar{2}\,2)$ MQW shows a high internal quantum efficiency. Possible reasons for this are weaker internal electric fields and a well thickness as thin as 1 nm. This thin well thickness prevents misfit dislocations from being introduced into the QW even with a high In composition, that is, in the region emitting red.

4. Conclusions

Successful growth of InGaN/GaN MQWs was achieved on $(1\,1\,\bar{2}\,2)$ facets of ELO GaN. Periodic MQWs structure was confirmed by TEM and XRD. TEM showed that the average growth rate on $(1\,1\,\bar{2}\,2)$ facet is lower than on (0 0 0 1) plane by a factor of 0.17. Micro PL spectra had investigated that our ELO InGaN/GaN MQWs structures provide wide range wavelength output light; this is suitable for the white color luminescence display devices. These properties make us believe that our proposed structure is promising for light-emitting devices that require sophisticated syntheses of colors such as pastels and white.

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