Multiwavelength emitting InGaN/GaN quantum well grown on V-shaped GaN (1 1 01) microfacet

Jin-Woo Ju¹, Lee-Woon Jang¹, Seung-Jae Lee², Jong Hyeob Baek² and In-Hwan Lee¹

¹School of Advanced Materials Engineering and Research Center for Advanced Materials Development, Chonbuk National

University, Chonju 561-756, Republic of Korea

Phone: +82-63-270-2292 E-mail: ihlee@chonbuk.ac.kr

²LED device team, Korea Photonics Technology Institute, Gwangju 500-460, Republic of Korea

1. Introduction

The epitaxial lateral overgrowth (ELOG) is a promising technique for obtaining a high-quality epitaxial layer with low threading dislocation density [1]. Especially, the ELOG GaN can be shaped with either rectangular or triangular cross-section by changing growth conditions [2]. In this work, InGaN/GaN MQWs were successfully grown on the inclined GaN ($1\bar{1}01$) microfacets. Conventional photolithography followed by regrowth of GaN was adopted to generate the V-shaped ($1\bar{1}01$) microfacets along $\langle 11\bar{2}0 \rangle$ direction. Cathodoluminescence (CL) spectra obtained from the microfacets revealed a nonuniform color distribution along the microfacets. This work proposes the novel route to fabricate a monolithic white light emitting diode without phosphors by controlling the growth of the InGaN/GaN MQWs on ($1\bar{1}01$) facet.

2. Experimental details

The ELOG structures were grown on (0001) plane sapphire (Al₂O₃) substrates by MOCVD (Veeco D180 GaN). Trimethylgallium (TMGa), trimethylindium (TMIn) and ammonia (NH₃) were used as precursors for Ga, In and N, respectively. Prior to the growth, sapphire substrates were heated to 1125 °C in hydrogen ambient for 5 min for removal of surface contaminants. A 30 nm thick GaN nucleation layer was grown at 530 °C, followed by growth of nominal 1.5 µm thick undoped GaN layer and 2.5 µm thick Si-doped n-type GaN at the elevated temperature of 1048 ^oC. After the first MOCVD growth, a 100 nm-thick SiO₂ film was deposited by plasma-enhanced chemical vapor deposition (PECVD) on the underlying GaN. Conventional photolithography and reactive ion etching (RIE) were used to form patterned stripes. The photomask was designed to have 4 sections of different patterns in 2 inch wafer. The sample was then loaded in to the MOCVD chamber to form V-shaped GaN $(1\overline{1}01)$ microfacets along $(11\overline{2}0)$ directions. The growth was carried out at 1033 °C and 200 torr for 3 hours with V/III ratio of 1700. Subsequently, five periods InGaN/GaN MQWs were grown at 750 °C (well) and 850 °C (barrier), respectively. Finally the MQW was capped with a 100 nm-thick undoped GaN layer. N2 gas was used as the carrier gas during the growth of the MQW active region in order to enhance the efficiency for indium incorporation, while H₂ gas was used as the carrier gas to grow the remaining parts of the sample. Four samples were prepared for comparison. Samples were grown with different window/mask width of 4/4, 4/7 and 4/10 μ m (labeled as sample A, B, and C, respectively) along the GaN $\langle 11\overline{2}0 \rangle$ directions. Sample D was grown on 4/7 μ m stripe along $\langle 1\overline{1}00 \rangle$ direction.

3. Results and discussion

Figure 1 shows the cross-sectional SEM images of the V-shaped GaN (1101) microfacets along $\langle 1120 \rangle$ directions for different mask width. The height of the pyramidal GaN was increased with increasing mask width. On the other hand, the (0001) plane was broadened by decreasing mask width. These different morphologies can be attributed to the difference in vertical and lateral growth rates after the coalescence of the base area has taken place. At first, only the V-shaped GaN (1101) microfacets were facilitated to grow until the neighbor GaN facets were joined. After that the lateral growth rate was accelerated, which led to gradual broadening of the top (0001) area. Thus, V-shaped GaN grown on the narrow mask width has a wider (0001) plane because neighbor GaN facets meet earlier. Sample D revealed a fully coalesced rectangular cross section (not shown here) as is expected for ELOG with $\langle 1\,1\,00\rangle$ stripe.



Fig. <u>1</u> Cross-sectional SEM images of the V-shaped GaN (1101) microfacets along $\langle 1120 \rangle$ directions for different mask width: a)4 µm, b)7 µm, and c) 10 µm.

To futher investigate the interfacial structure of In-GaN/GaN MQWs on the GaN facet, TEM was performed. Figure 2 shows the cross-sectional TEM images of sample C viewed along the $\langle 11\overline{20} \rangle$ direction. The clear interfacial contrast indicates that the MQW was successfully formed on the GaN facets and the thickness of MQW barrier was varied with position. The thickness of InGaN well was invariant to be 1.7 nm. The GaN barrier thickness in the upper and lower part was 3.8 nm and 5.8 nm, respectively. It was observed that the thickness of the barrier layer is position dependent, but the reason for such dependence is not clear.

It is noteworthy that the growth rate of the well and the barrier on (1101) facet is significantly smaller than that

on (0001) plane. For the growth of InGaN/GaN MQW, we applied the same growth recipe as a blue LED that aimed at well and barrier thickness of 2.5 nm and 15 nm, respectively. This different growth rate can be attributed to the fact that the incorporation efficiency of subsequent atoms at the growth front depends on crystallographic orientation [3].



Fig. 2 Cross-sectional TEM images viewed along the $\langle 1120 \rangle$ direction, showing (a) entire region and (b) magnified image of area on the (1101) facet.

Figure 3 shows the position dependence CL spectra for sample A measured at room temperature. As the e-beam is moved from the bottom to the top edge of the facet, a 20 nm red-shift (from 420 nm to 440 nm) for the MQW emission peak wavelength was observed, leading to the distinct C-shaped peak position. This is an interesting observation because it suggests a monolithic white LED without phosphors can be fabricated by growing the MQWs on $(1 \overline{1} 01)$ facet and controlling the parameters such that emission of different wavelengths will be possible. Srinivasan *et al.* reported that the spatial variation in the CL wavelength was caused by the variation in well width along the slope of the GaN facet [4].



Fig. 3 Room temperature CL spectra measured on the microfacets at different positions as indicated in the left SEM image.

In this work, the well thickness is uniform and the barrier thickness is different along the facet. We consider that the CL peak shift along the facet may be caused by the change in barrier thickness (4–6 nm). The barrier is thin enough to

allow the adjacent wave function to overlap [5]. The wave function overlapping between adjacent wells may cause the red-shift of CL peak, which will be larger with decreasing barrier thickness. Nishizuka *et al.* and Zhang *et al.* attributed the evolution of peak position to In compositional variation in the QW along the facet because of a longer migration length of In than Ga [6,7]. Therefore, in-depth compositional analysis is needed to clarify the reason for the C-shaped peak evolution, as the possibility of In compositional variation along the facet can not be ruled out at this moment,

3. Conclusions

We have investigated the growth of InGaN/GaN MQWs formed on V-shaped GaN $(1\overline{1}01)$ microfacet. The clear TEM interfacial images indicated that the MQW was successfully grown on the GaN facets. CL measured on the microfacets showed a continuous change of the luminescence peak positions. The CL peaks were shifted to a longer wavelength from 420 nm to 440 nm as the probing points changed. This could be attributed to the non-uniform distribution of the In composition and/or the wave function overlapping between adjacent wells. We believe that by controlling growth parameters and mask geometries, not only the overall difference between the peak positions can be further increased but also a desired wavelength can be produced. Present works thus propose the fabrication of a monolithic white light emitting diode without phosphors by growing the InGaN/GaN MQWs on $(1\overline{1}01)$ facet.

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