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Fabrication and optical properties of nano-structured semipolar InGaN/GaN quantum wells on c-plane GaN template

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High density self-assembled nanostructured semipolar (NSSP) GaN pyramids are fabricated based on *c-plane* GaN template by *in situ* silane treatment followed by high temperature treatment. Semipolar InGaN/GaN multiple quantum wells (MQWs) were subsequently grown on the NSSP GaN. Optical properties of the MQWs were studied by temperature-dependent and excitation density varied photoluminescence. It was found that the internal electric field in the NSSP MQWs were remarkably reduced in comparison with planar *c-plane* MQWs. The internal quantum efficiency of the NSSP MQWs was measured to be > 30% which showed potential applications in III-nitride light emitters.

1 Introduction Owing to the lack of the inversion symmetry, wurtzite III-nitride based heterostructure exhibits a strong internal electric field (IEF) due to spontaneous and strain-induced piezoelectric polarization along the crystallographic *c-axis*, leading to the spatial separation of wave functions for electrons and holes in quantum wells, which results in a reduction of the oscillation strength and the suppression of radiative recombination efficiency [1-3]. To overcome these issues, nonpolar and semipolar III-nitride heterostructures have attracted a lot of attentions due to their potentials in completely or partially eliminating the IEF [4-9]. Unfortunately, planar nonpolar and semipolar light emitting diodes (LEDs) grown on foreign substrates by hetero-epitaxy still suffer from higher density of crystalline defects, which deteriorates the device performance and lowers the light emitting efficiency in comparison with those grown on *c-plane* sapphire or SiC substrates [10, 11]. Recently, homo-epitaxially grown LEDs on free-standing bulk nonpolar and semipolar GaN substrates showed comparable performance in comparison to the state-of-the-art *c-plane* LEDs [12, 13], which clearly indicated the importance of crystal quality in realizing high performance nonpolar and semipolar light emitters. However, experimental nonpolar and semipolar GaN substrates have small sizes and are sliced from hydride vapor phase epitaxy (HVPE) grown GaN. To date, there is still no cost-effective technique to achieve high quality nonpolar and semipolar GaN templates.

In this letter, we report a novel fabrication of nano-structured semipolar (NSSP) GaN based on technically mature *c-plane* GaN epi-layers. Optical studies of the semipolar InGaN/GaN MQWs, which are subsequently grown on the NSSP GaN, show a remarkably reduced IEF and high internal quantum efficiency (IQE).

2 Experimental Samples were grown on *c-plane* sapphire substrate by low pressure metalorganic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa), Trimethylindium (TMIn) and ammonia (NH_3) were used as the precursors for Ga, In and N, respectively. First, a 2 μm-thick unintentionally doped GaN film was grown at 1050°C on a 25 nm-thick GaN nucleation layer deposited at 500°C. Then, the TMGa source was switched off and 40 sccm of diluted SiH_4 (50ppm in H_2) was introduced into the reactor for 300 sec, hereinafter referred to as the *in situ* silane treatment (ISST), which results in a rough GaN surface characterized by high density of truncated cones as shown in Fig. 1. The details of the ISST process and the induced morphological change on GaN surface will be published elsewhere [14].

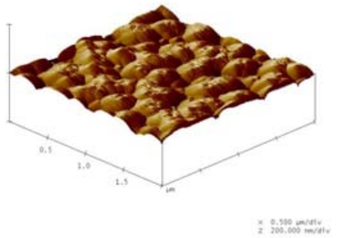
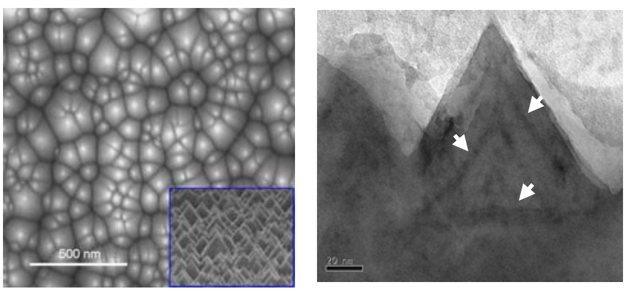


Figure 1 The atomic force microscopy (AFM) 2×2 μm image of the GaN surface after the ISST process. The room-mean-square (RMS) roughness is measured to be 10 nm.

After the ISST process, the reactor temperature was increased to 1080-1100 °C, and the TMGa was switched on for 600 sec, hereinafter referred to as the high temperature treatment (HTT). During both the ISST and HTT processes, the sample was kept under the NH_3 flow. After the two-step process, high density nanostructured semipolar (NSSP) GaN pyramids are self-formed on the *c*-plane GaN template as confirmed by the scanning electron microscopy (SEM) characterization, which is shown in Fig. 2(a). Subsequently, three periods of InGaN/GaN MQWs were grown on the NSSP GaN at 770 °C. For comparison, another three periods of InGaN/GaN MQWs were also grown on the planar *c-plane* GaN template. The surface morphologies and optical properties of these two samples were characterized by the field-emission SEM and photoluminescence (PL) measurements using a He-Cd laser at a wavelength of 325 nm.

3 Results and discussion In Fig. 2(a), the SEM image of the NSSP GaN is shown. The surface of the as-treated GaN film consists of compact cluster-like structures with dimensions in the range of 100 to 200 nm. It is noticed that there exists a relatively bright point in the center of the each cluster, which corresponds to the tip of the nano-scale pyramid as shown in the bird's eye view (inset of Fig. 2(a)). Fig. 2(b) shows the cross-sectional high resolution transmission electron microscopy (HR-TEM) image of the MQWs structure grown on the NSSP GaN.



(a) (b)

Figure 2 (a) The SEM image of the NSSP GaN fabricated on the *c-plane* GaN template, the inset shows the bird's eye view. (b) Cross-sectional HR-TEM image of the NSSP InGaN/GaN MQWs grown on NSSP GaN. The InGaN wells are marked by the white arrows.

The three quantum wells are observed as darker lines and are marked by the white arrows. The thickness of the InGaN well and the GaN barrier are measured to be 5 and 15 nm, respectively, which agrees with the nominal values characterized by the planar MQWs growth. In addition, the angle between the inclined surface and the *c-plane* is also measured. Both 63° and 58° planes exist on the same sample. We identify those planes as (10-11) and (11-22) semipolar planes [7]. Because the MQWs are grown on inclined surfaces, the total light emitting area is about 2 times as high as that of the corresponding *c*-plane MQW. Mean while, the number of threading dislocations can be considered remain the same during the ISST and HTT processes. Therefore the density of threading dislocations in the active region was expected to be decreased roughly by a factor of two, which may furthermore increase the IQE.

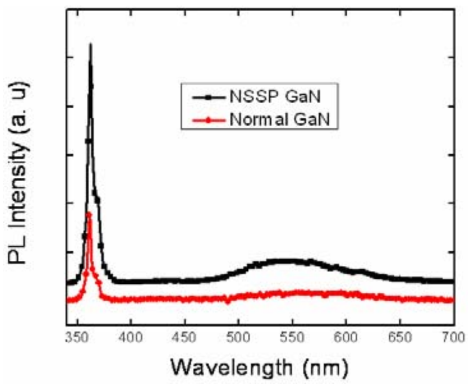


Figure 3 Room temperature PL spectra of both NSSP GaN and planar *c-plane* GaN.

Optical properties of the NSSP GaN are investigated by room temperature (300 K; RT) PL and are compared to a 2 μm-thick planar *c*-plane GaN film. As shown in Fig. 3, both RT-PL spectra are dominated by a sharp near band-edge (NBE) emission at 362 nm and weak yellow band luminescence. The NBE emissions have comparable line-width of 41.2 meV and 36.6 meV for the NSSP GaN and the planar GaN, respectively. Moreover, the PL intensity of NBE emission for the NSSP GaN is about three times as high as that measured for the planar GaN film. The mechanism of the increasing PL intensity for the NSSP GaN is still under investigation, but it can be partly attributed to the surface roughing of the NSSP sample, which leads to the improvement of the light extraction efficiency by reducing the total internal reflection of photons at the air-semiconductor interface [14, 15].

Figure 4 shows the PL spectra as the function of the excitation power density for InGaN/GaN MQWs on both *c-plane* (a) and NSSP (b) GaN. As expected, the PL peak energy of the *c-plane* MQWs shows an obvious blue-shift (472 nm to 460 nm with an increasing excitation power density from 2.0 W/cm^2 to 2.5 kW/cm^2) due to screening of carriers for the IEF. While for the MQWs on NSSP GaN,

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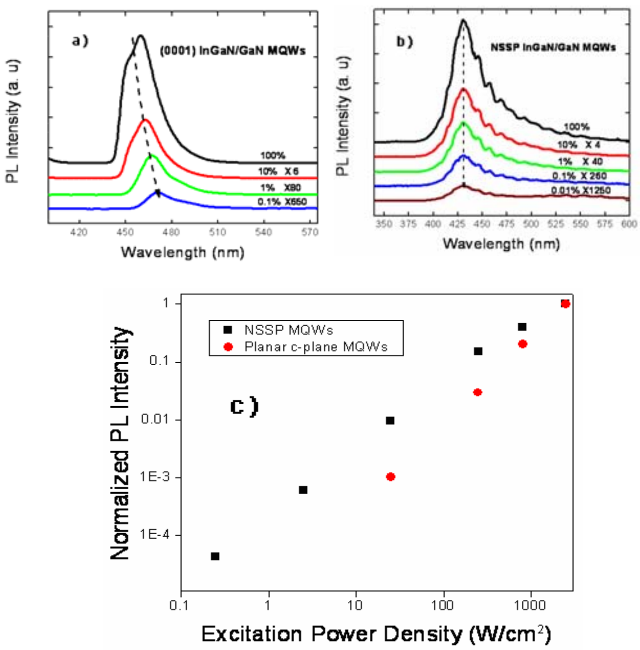

Figure 4 Room temperature PL spectra as the function of the excitation power density for (a) the planar *c*-plane InGaN/GaN MQWs; and (b) the NSSP InGaN/GaN MQWs. (c) The PL intensity as the function of the excitation power density for both NSSP and *c*-plane InGaN/GaN MQWs.

negligible wavelength shift is observed, which is likely due to the reduction of IEF on semipolar planes. It is also worthwhile to notice that as we decrease the excitation power density, the reduction of the PL intensity in the NSSP MQWs is much slower than that in the *c-plane* MQWs as shown in Fig. 4(c). This is because with the reduction of the excitation power density, the weakened IEF in the *c*-plane MQWs by the screening of photo generated carriers is recovered gradually, which leads to the lowering of radiative recombination efficiency.

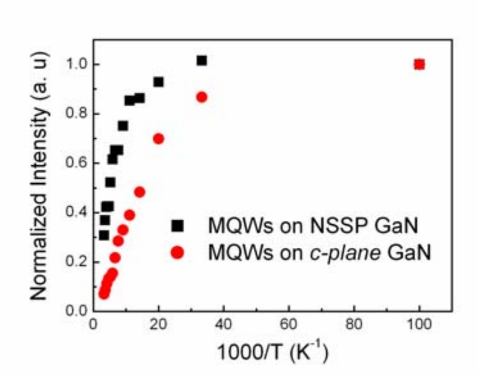

Figure 5 Temperature dependence of the integrated PL intensity for NSSP InGaN/GaN MQWs (Arrhenius plot).

Temperature-dependent PL was carried out to evaluate the IQE of the InGaN/GaN MQWs grown on NSSP and *c-plane* GaN. Figure 5 shows the Arrhenius plots of the integrated PL intensity for InGaN/GaN MQWs in the temperature range of 10-300 K. Assuming the IQE is equal to 100% at low temperature (10 K), the IQE of NSSP MQWs is deduced to be 30.2% at RT, which is higher than that of *c-plane* MQWs, as shown in Fig. 5. This value is expected to be further improved by careful optimization of the growth conditions.

4 Conclusion In conclusion, we report a novel approach to fabricate nanostructured semipolar GaN on the planar *c-plane* GaN template using *in situ* silane followed by high temperature treatments. InGaN/GaN MQWs are subsequently grown on the NSSP GaN. It is found that the IEF of the NSSP MQWs are remarkably reduced in comparison with that in the planar *c*-plane MQWs. The experimental measurement of the IQE for the NSSP MQWs shows that it is a promising technique to obtain high performance light emitters.

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