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Fabrication and Characterization of Three Dimensional Semipolar {10-11} and Nonpolar {10-10} Core-shell InGaN/GaN Multi-Facet Quantum Wells Optoelectronics Devices

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1. Introduction

In recent years, one dimensional GaN nano structures have gained significant research interests as a potential alternative design to improve the efficiency of the commonly used planar GaN light emitting diodes (LEDs). The nanopillar structure provides several advantages over the planar structure. The nanopillar exhibits a significantly reduced defect density because it has only a small area of contact with the growth template. This small footprint reduces strain built up from the lattice and thermal expansion coefficient mismatch between the GaN nanopillar and the growth template[1-3], thus reducing piezoelectric polarization and improving electron-hole recombination efficiency.[4,5] The nanopillar offers an additional option to grow MQWs on the pillar surfaces in a core-shell geometry. These surfaces can be nonpolar or semipolar crystal planes with zero or low polarization fields. The MQWs grown on these planes have lower carrier density dependent wavelength change and higher radiative recombination efficiency.[6-8] Due to the nature of their three dimensional structure, the growth and emission properties of core-shell MQWs can vary with different crystal planes and require investigation.

2. Experiments

Fig. 1(a)-(c) showed the schematic fabrication processes and Fig. 1(d)-(e) showed the corresponding scanning electron microscope (SEM) images. The nanorod arrays were fabricated from a GaN epitaxial template by nano imprint patterned etching and followed by epitaxial regrowth. A 2 μm GaN layer was grown by AXITRON 2000HT metalorganic chemical vapor deposition (MOCVD) reactor on a *c*-plane sapphire substrate. A 0.3 μm SiO_2 thin film was deposited by plasma-enhanced chemical-vapor deposition (PECVD) and fabricated by nano imprint lithography. The SiO_2 disks were used as masks in inductively coupled plasma reactive ion etching (ICP-RIE) to etch down exposed GaN and form GaN nanorods (Fig. 1(a)). These disks were subsequently removed by buffer oxide etch (BOE). A SiO_2 thin film was then grown conformally on the nanorod template by PECVD, followed by RIE etch to expose the top of nanorods. The GaN base layer and the bottom of GaN nanorods were protected by SiO_2 thin film (Fig.1(b)). The GaN nanorod samples were reloaded into MOCVD rector. The regrowth process formed the crystalline facets on the etched nanorod surfaces, as shown in Fig. 1(c). Six pairs of InGaN/GaN multiple quantum wells (MQWs) were grown on the nanorod crystalline facets. The growth temperature for wells and barriers were 830℃ and 900℃, respectively, and the growth pressure was 300mbar. The fabricated nanorod has {10-10} sidewalls and {10-11} pyramid facets, as shown in Fig. 1(e) and (d).

For time resolved photoluminescence (TRPL) measurement, the sample was mounted in the closed-cycle He cryostate and temperature was controlled from 15k to 300K. A frequency doubled femto-second-pulse Ti-sapphire laser of 400 nm was used as an excitation light source.

3. Results and discussion

Fig. 2 shows the time-resolved photoluminescence (TRPL) measurement of the coreshell nanorods. The PL lifetime of the nonpolar {10-10} blue emission from the sidewall at (a) 15K and (b) 300K were 0.68s and 0.3s, respectively. The PL lifetime of the semipolar {10-11} green emission from the pyramidal top at (c) 15K, (d) 300K were 0.83s and 0.48s, respectively. The faster recombination lifetime of blue emission on nonpolar {10-10}, as compared with the green emission on semipolar {10-11}, was due to the lower In content and no spontaneous polarization filed.

Fig. 3 shows the measured temperature dependent PL lifetime (τ_{PL}), and the derived radiative lifetime (τ_r) and non-radiative lifetime (τ_{nr}) by Eq (1) and (2):

$$\tau_r(T) = \frac{I_{PL}(LT)}{I_{PL}(T)}\tau_{PL}(T) \ldots\ldots\ldots (1)$$

$$\frac{1}{\tau_{PL}} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \ldots\ldots\ldots\ldots (2)$$

The measured radiative lifetime at room temperature for nonpolar (10-10) blue MQWs and semipolar (10-11) green MQWs were 1.47ns and 1.79ns, respectively. These τ_r values are about two orders of magnitude smaller than the typical values reported for *c*-plane (0001) MQWs. The faster radiative recombination is the strong evidence to the suppression of polarization field in InGaN/GaN MQWs. The measured τ_{nr} is also significantly shortened as well. It is attributed to smaller potential localization for MQWs grown on the semipolar and the nonpolar facets.

Fig. 4 shows the temperature dependent behavior of radiative lifetime (τ_r) of both nonpolar (10-10) blue emission and semipolar (10-11) green emission. It is about constant below 70K and increases linearly above 100K. This behavior can be described by the fact that the radiative life-time is proportional to density of states, which has a temperature dependence depending on the physical geometry of the source as described in the following equation:

$$\tau_r \propto DOS \propto T^{0.0}\ (0D)$$
$$\tau_r \propto DOS \propto T^{0.5}\ (1D)$$
$$\tau_r \propto DOS \propto T^{1.0}\ (2D)$$
$$\tau_r \propto DOS \propto T^{1.5}\ (3D)$$

At low temperature, the excitons are trapped in localized potentials due to inhomogeneous In composition in MQWs. It behaves as a single quantum dot, therefore, has constant radiative lifetime. As temperature increases, excitons are excited out of the traps and become free excitons in the 2D MQWs, resulting in approximately linearly increasing radiative lifetime.

4. Conclusions

In conclusions, the core-shell InGaN/GaN MQWs grown on top-down etched GaN nanorods composed the semipolar {10-11} pyramidal top and the nonpolar {10-10} hexagonal sidewalls. The measured radiative lifetime at room temperature for nonpolar (10-10) blue MQWs and semipolar (10-11) green MQWs were about two orders of magnitude smaller than the typical value reported for c-plane (0001) MQWs. The faster radiative recombination is the strong evidence to the suppression of polarization field in InGaN/GaN MQWs. As the temperature increased, the free excitons in the 2D MQWs results in approximately linearly increasing radiative lifetime.

Acknowledgements

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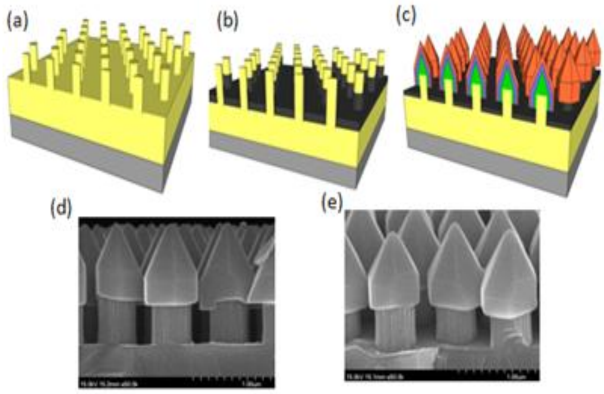

Fig. 1 The schematic pictures of (a) the etched nanorods on GaN template, (b) the oxide passivation on the bottom of GaN nanorods and the GaN base layer, and (c) the regrown coreshell nanorod structure, respectively. The corresponding SEM image viewed in (d) cross-section and (e) 45°, respectively.

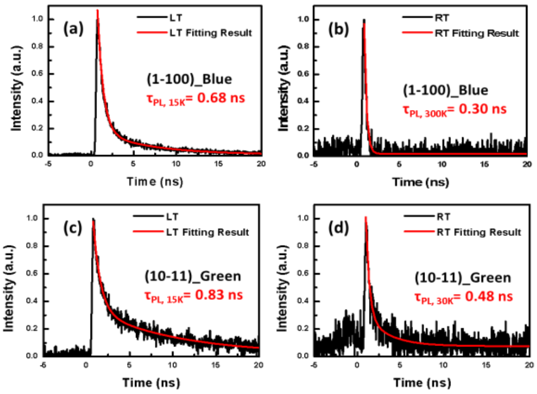

Fig. 2. TRPL measurement of the nonpolar (10-10) blue emission at (a) 15 K, (b) 300K and the semipolar (10-11) green emission at (c) 15 K, (d) 300K.

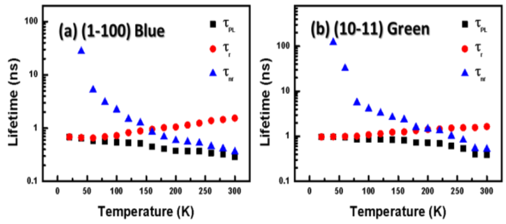

Fig. 3. τ_{PL}, τ_r and τ_{nr} versus temperature of (a) the nonpolar (10-10) blue emission and (b) the semipolar (10-11) green emission

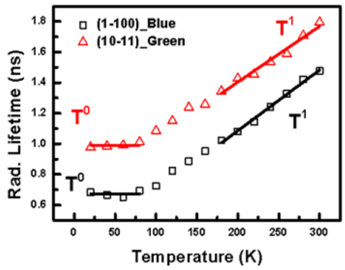

Figure 4. Radiative lifetime (τ_r) and the fitting curve for dimensional of excition of both nonpolar (10-10) blue emission and semipolar (10-11) green emission.

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