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InGaN/GaN Multi-Quantum-Well Nanorods Fabricated by Plasma Etching Using Self-assembled Nickel Nano-masks

Tao-Hung Hsueh[1], Hung-Wen Huang[1], Chih-Chiang Kao[1], Ya-Hsien Chang[1], Miaochia Ou-Yang[1], Hao-Chung Kuo[1] and Shing-Chung Wang[1]

[1] Institute of Electro-Optical Engineering, National Chiao Tung University
1001, Ta Hsueh Road, Hsinchu 300, Taiwan ROC
Phone: +886-3-5712121 ext.56320 E-mail: scwang@cc.nctu.edu.tw

1. Introduction

Nitride-based semiconductors are recognized as the major direct bandgap materials for a lot of applications in the areas of optoelectronic devices and high-temperature / power electronic devices such as UV or blue emitters and detectors [1]. Recently, the fabrication and optical characterization of the one-dimensional (1D) gallium nitride (GaN) nanostructures have attracted a great deal of interest for fundamental research and potential applications. Up until now, the GaN nanorods have been produced by various fabricated techniques, such as inductively coupled plasma reactive ion etching (ICP-RIE) without mask [2], synthesis using carbon nanotubes as templates [3], growth of single-crystal GaN nanorods by hydride vapor phase epitaxy [4] and so on. However, all of these reported methods are relatively complicated and their structures are not for devices. For achieving nano-light-emitting device, it is necessary to develop further on fabrication techniques of heter- or LED nanostructure. In this article, we report a novel method to fabricate high-density InGaN/GaN MQW nanorods by ICP-RIE dry etching technique using self-assembled nickel (Ni) nano-masks.

2. Experiment

The III-nitride materials used were grown by metal-organic chemical vapor deposition (MOCVD) on c-axis sapphire substrate with 30 nm GaN buffer layers. The structure consists of a 3.0 μm of silicon doped GaN, 0.1 μm five-period InGaN active layer, and 0.1 μm magnesium (Mg) doped p-type GaN. The size of each sample used in this study was about 2.5×2.5 cm^2. Fig. 1 is the process flowchart of the InGaN MQW nanorods. First, a 3000 Å-thick Si_3N_4 thin were deposited on the samples using photo enhanced chemical vapor deposition (PECVD), and then followed by the deposition of 50, 100, and 150 Å-thick Ni layer respectively by electron-beam evaporation system. Then the samples were treated with rapid thermal annealing (RTA) of 850 degree under nitrogen ambiance for one minute to form self-assembled Ni nanosized masks or clusters. After nanosized masks formation, the reactive ion etching (RIE) was processed using CF_4/O_2 gases to etch Si_3N_4 film. Then the samples were etched down to the n-type GaN layer by ICP-RIE (SAMCO ICP-RIE 101iPH) Finally, the remain of nano-masks was removed in buffer oxide etchant and the fabrication of InGaN/GaN MQW nanorods were finished.

3. Results and discussion

It is known that the thickness of the Ni film can play an important role in determining Ni nanometer clusters at a given temperature. Fig. 2 shows the mean dimension and density of InGaN-based nanorods as a function of Ni-mask initial layer thickness from 50 to 150 Å. As the Ni clusters get larger (nano-masks dimension increase) the nano-masks become more dispersed resulting in fabricating smaller and denser nanorods. As the Ni initial thickness decrease, migration from Ni film to islands was more easily and Ni clusters dimension size become smaller at the same annealed condition.

The scanning electron microscope (SEM) image of the finished InGaN/GaN MQW nanorods fabricated by the ICP-RIE dry etching using self-assembled Ni nano-masks is shown in Fig. 3. Taking the room-temperature lattice constant of Ni to be 3.52 Å and that of the corresponding crystalline Si_3N_4 surface to be 7.61 Å in the a direction and 2.91 Å in the c direction gives the room temperature strains as $\varepsilon_{a(Si3N4/Ni)}$= -53% and $\varepsilon_{c(Si3N4/Ni)}$ =21% respectively [5]. This means that the deposition of Ni on Si_3N_4 results in a large degree of compressive in the c direction and tensile strain in the direction. So the nanosized Ni clusters or islands formed on surface during thermal treatment.As shown in Fig. 3, the mean dimension and density of the nanorods were about 80~100 nm and 1.5×10^{10} cm^{-2} respectively. In addition, the shapes of these nanorods are almost vertical and uniform.

The transmission electron microscopy (TEM) (JEOL, JEM-200CX) image of a single InGaN/GaN MQW nanorod is illustrated in Fig. 4. It shows clearly that the diameter and length of a single nanorod are approximately 80 nm and 1 μm. The active region of five-period MQW is also observed evidently from the TEM image. The width of the quantum well and barrier are estimated to be about 5 and 25 nm.

The emission peaks of room temperature He-Cd photoluminescence at 451 and 446 nm for the bulk and nanorods respectively are observed as showed in Fig4. The large (about 30 meV), distinct blueshift of the band edge emission could be attributed to the partial strain relief in the well [6]. Other groups reported the blueshift in GaN nanorods and GaAs nanowires compared to bulk material which were attributed to quan-

tum confinement effect [4] [7]. Additionally, the PL intensity in the nanorods is enhanced by a factor of about 5 times. The enhancement is can be due to the better overlap of the electron and hole wave functions with a reduced piezoelectric field, and increasing of the radiative recombination rate. Moreover, the light scattering off the etched sidewalls after dry etching can also increase the PL intensity in the InGaN/GaN MQW nanorods.

4. Conclusions

High density (1.5×10^{10} cm^{-2}) InGaN MQW nanorods with diameter of 80~100 nm have been fabricated by plasma etching using self-assembled Ni nano-masks. The nanorods show an intense emission of 446 nm that exhibits a clear blueshift of 30 meV from the bulk, indicating the partial strain relief in the nanorods. The enhancement in emission intensity of the nanorods by a factor of 5 times compared with the bulk is also observed in this study. It should be applicable for fabrication of III-V based nano-light-emitting device.

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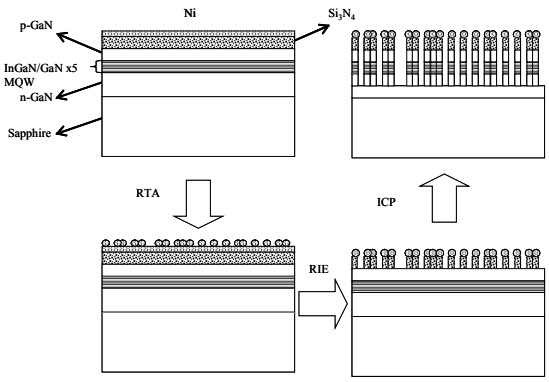

Fig. 1 Schematic diagram showing the process of InGaN nanorods using self-assembled Ni nano-masks and ICP-RIE etching.

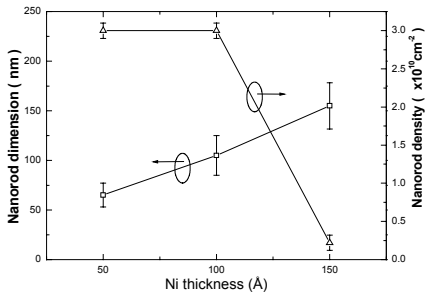

Fig. 2 The mean dimension and density of InGaN MQW nanorods as a function of Ni film thickness at 850 ºC of RTA for 1min.

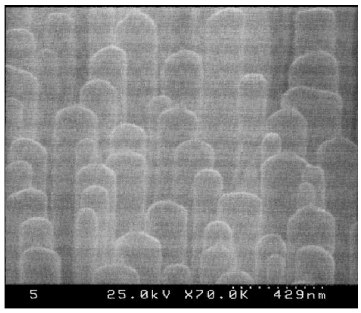

Fig. 3 The SEM image of InGaN MQW nanorods fabricated by ICP-RIE etching using self-assembled Ni nano-masks.

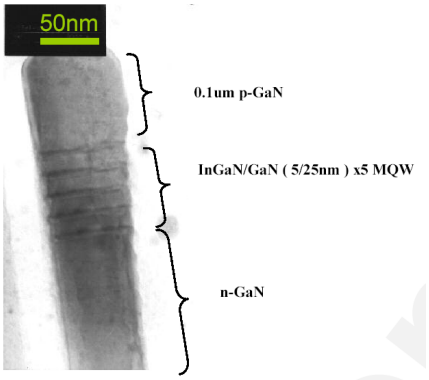

Fig. 4 Transmission electron micrograph of a single InGaN MQW nanorod.

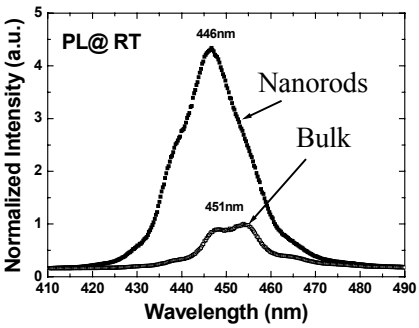

Fig. 5 Room temperature He-Cd PL spectra of InGaN MQW nanorods and bulk.