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Characteristics of nanoporous InGaN/GaN multiple quantum wells

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The nanoporous InGaN/GaN multiple quantum wells (MQWs) has been fabricated through rapid thermal annealing (RTA) and inductively coupled plasma (ICP) dry etching process using self-assembled Ni nanoporous masks. In comparison with the as-grown planar InGaN/GaN MQWs, both internal quantum efficiency and light extraction efficiency for nanoporous InGaN/GaN MQWs are increased, which can be concluded from the photoluminescence (PL) measurements. The thermal activation energy of nanoporous structure (107.44 meV) is significantly higher than that of the as-grown sample (33.02 meV) from temperature-dependent PL measurement, indicating that carriers are well confined and the non-radiative recombination caused by the dislocations and other defects has been reduced. Besides, enhanced light scattering in the disordered nanoporous system can further increase the output emission intensity. The enhanced performance of nanoporous InGaN/GaN MQWs reveals its promising applications for high-efficiency light-emitting devices.

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1. Introduction

III-nitride-based semiconductors have attracted a lot of attention for the fabrication of solar-blind ultraviolet detectors, laser diodes, and high power electronic devices in the last two decades. InGaN/GaN multiple quantum wells (MQWs) have been used as active layers for blue, green, and white light emitting diodes (LEDs) and laser diodes (LDs) [1–5]. Due to the large lattice mismatch and the difference in thermal expansion coefficients between the epilayer and the substrate, high density (10^8–10^{10} cm^{-2}) of threading dislocations and other crystalline defects originating at the film/substrate (or film/buffer layer) interface and propagating through the entire InGaN/GaN MQW structure. These threading dislocations and other crystalline defects are acted as nonradiative centers [6,7] to reduce the internal quantum efficiency.

Recently, in an attempt to minimize the density of dislocations and other defects for improving internal quantum efficiency for InGaN based MQWs, a lot of methods such as homoepitaxy growth on GaN single crystal substrates [8], epitaxial layer overgrowth [9,10], multiple intermediate layers [11] have been demonstrated. However, these techniques are extremely expensive and difficult to reduce the dislocation density to be less than 10^6 cm^{-2}. In addition, the fact that they are highly non-uniform and small in size also makes them unsuitable for mass production.

In order to obtain high performance and highly reliable nitride-based optoelectronic devices, effective, affordable, large area, and low threading dislocation (TD) density materials or device structures are demanded. Fabrication of nanostructured InGaN/GaN based optoelectronic devices is one of a promising approaches to reduce the dislocation density for further improving the devices' performance, such as fabrication of InGaN/GaN based LEDs into nanorod arrays [12,13] and nanotips [14]. In addition, by reducing the size of the emitting area to nanostructures with a higher surface area are also helpful for increasing the light extraction efficiency. As a result, low-dislocation density nanostructures can improve both internal quantum efficiency (η_{int}) and light extraction efficiency (η_{ext}).

In this letter, we report on the fabrication and characterization of the nanoporous InGaN/GaN MQWs. The nanoporous InGaN/GaN MQWs are fabricated by inductively coupled plasma (ICP) top-down etching using self-assembled Ni nanoparticle masks on a planar InGaN/GaN MQW structure. The optical properties of the nanoporous InGaN/GaN MQWs and as-grown planar samples are investigated by means of photoluminescence (PL). From the results, enhanced performance of nanoporous InGaN/GaN MQWs is obtained compared with the as-grown MQW sample, attributing to the effects of drastic reduction of dislocations and defects.

2. Experimental details

InGaN/GaN MQW structure was grown on a (0001) sapphire substrate in a metalorganic chemical vapor deposition (MOCVD) system. On top of the substrate, a 30 nm thick low-temperature GaN buffer layer and a 2-μm thick Si-doped GaN epitaxial layer were grown, followed by a MQW structure with five periods of $In_{0.15}Ga_{0.85}N$/GaN MQWs (2 nm wells and 8 nm quantum barriers) as the emitting layers. The barrier layers were grown at 825 °C and the wells were grown at 745 °C. Finally, the MQW structure was terminated with the deposition of a 10-nm thick GaN cap layer.

After the epitaxial growth, the nanoporous InGaN/GaN MQWs were fabricated by using self-assembled Ni nanomasks. For the nanoporous fabrication process, firstly, a 6 nm Ni layer was deposited on top of the InGaN/GaN MQWs by electron beam evaporation. Next, the Ni-coated MQW sample was subsequently subjected to rapid temperature annealing under N_2 atmosphere at 800 °C for 30 s to form self-assembled nickel nanomask. And then, the sample was etched down by the ICP system (Oxford Plasma System 100, ICP 180) using Cl_2/BCl_3 gas. Finally, the nanoporous MQWs were immersed in 50% HCl solvent to minor the damages caused by the dry etching, which has been reported previously in Ref. [15].

The surface morphology was examined by field emission scanning electron microscopy (FE-SEM). The optical properties of the samples were investigated by temperature dependent photoluminescence measurements. The samples to be measured have been placed in an evacuated cryostat for