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Room Temperature Operation of GaAs/AlGaAs Quantum Nanodisks Light Emitting Diodes Fabricated by Fusion of Bio-Template and Neutral Beam Etching

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Abstract

III–V compound semiconductor quantum dots photonic devices are very attractive for optical network, III-V monolithic and/or Si hybrid photonic integrate circuits. We developed a defect-free top-down fabrication process for sub-20-nm-diameter GaAs quantum nanodisks by using a bio-template and neutral beam etching. We successfully etched 80-nm-high nanopillars embedded in 12-nm-thick GaAs and 12-nm-thick $Al_{0.15}Ga_{0.85}As$ barrier-stacked structures. And then, $Al_{0.3}Ga_{0.7}As$ barrier layer and $Al_{0.25}Ga_{0.75}As$ upper cladding layer and GaAs capping layer were regrown by metalorganic vapor phase epitaxy. We could directly measure the electroluminescence (EL) originating from the GaAs QNDs light emitting diode at room temperature (RT).

1. Introduction

Quantum dots (QDs) as optical gain media have a great potential of a lot of interest because of desirable properties such as low threshold and low temperature sensitivity due to the discrete nature of the density of states. Uniform QDs and a high density of two-dimensional (2D) arrays with isolation are required when considering the photonic applications in telecommunication technology and information technology for III-V and silicon hybrid photonic integrated circuits, and optical data storage [1, 2].

To improve size dispersion and density, which cannot be precisely controlled by using self-assembly, a technique that integrates a bio-template [3] with neutral beam etching (NBE) [4] was used since it has great potential for fabricating defect-free high density (7×10^{11} cm^{-2}) sub-20-nm-diameter GaAs quantum nanodisk (QND) structures. This process uses 7-nm-diameter metal oxide cores inserted in a cage-like protein (ferritin) as the etching masks. NBE is used to etch GaAs wafers without defects in the nanostructures [5 - 7].

In this study, we fabricated room temperature operation of GaAs QND light emitting diodes (QND-LED) by etching a GaAs/AlGaAs stacked-layered structures, which were fabricated by MOVPE, using a bio-template and NBE.

2. Experiment

Figure 1 shows a schematic illustration of the neutral beam system. It consists of plasma and process chambers that are separated by an electrode with an aperture array. The electrode can effectively neutralize charged particles when the plasma particles pass through it and eliminate UV photons from the plasma. Thus, defect-free atomically flat sidewalls and anisotropic etching are observed after the neutral beam etching.

The fabrication process integrates a bio-template and neutral beam etching. Multiple quantum wells (MQWs) with 12-nm thickness were grown by MOVPE on n-doped GaAs substrates. The structure consisted of a 232-nm-thick n-GaAs buffer layer, 1um-thick p-$Al_{0.3}Ga_{0.7}As$ lower cladding layer, undoped-$Al_{0.25}Ga_{0.75}As$ SCH layer, 12-nm-thick undoped GaAs MQWs, clad on either side with barrier layers of 12-nm-thick $Al_{0.15}Ga_{0.85}As$, and a 10-nm cap of undoped GaAs. First, a sample was cleaned by organic treatment and by using deionized water in an ultrasonic bath to make the surface hydrophilic. We used ferritin modified with polyethylene glycol (PEG ferritin), which contains iron oxide cores, to make the distance between ferritins greater than 30 nm to eliminate the coupling of wave functions between GaAs NDs. Then, oxygen-annealing in vacuum was used to remove the ferritin protein shell at 350 ºC with oxygen. The remaining 7-nm diameter iron oxide cores were used as the etching masks. Hydrogen-radical treatment was used to remove the surface oxide. The samples were then etched by NBE with chlorine gas. After etching, the passivation of samples was conducted by hydrogen-radical treatment to prevent any surface oxidation.

After etching, the metal oxide cores were removed by using dilute hydrochloric acid. Finally, undoped $Al_{0.3}Ga_{0.7}As$ barrier, 100 nm-thick undoped $Al_{0.25}Ga_{0.75}As$ upper SCH, 1μm -thick p-$Al_{0.3}Ga_{0.7}As$ and 20nm-thick p-doped GaAs cap were regrown by annealing the sample at 700 ℃ and 610 ℃, respectively. MOVPE was used to fill the gaps between nanopillars. Finally, electrodes are deposited by common LED fabrication process.

3. Results and Discussion

We successfully fabricated high aspect ratio sub-20-nm-diameter nanopillars by chlorine NBE [8] and measured the EL from 12-nm-thick GaAs NDs, as shown in Fig. 2. Strong EL centered at 760 nm were observed for the 12-nm-thick GaAs QNDs. These observed peaks in the spectra were clearly distinguished from those of the GaAs MQWs. The emission energy of the NDs sample was blue-shifted by 40 nm compared with that of the 12-nm-thick GaAs MQWs. Figure 3 shows a comparison between 8-nm-thick GaAs QND-LED and 12-nm-thick GaAs QND-LED. 12-nm GaAs LED has performed at RT because of the quantum confinement energy level is deep from band edge of AlGaAs barriers.

4. Summary

We observed 8nm-thick and 12-nm-thick GaAs QND-LED operation produced by a defect-free fabrication process. This process resulted in the formation of high density sub-20-nm nanopillars with a large inter-dot distance (the distance between ferritins was greater than 20 nm) by using PEG ferritin, NBE, and MOVPE regrowth. The EL at RT shows that these fabricated QND-LED have immense potential for use in high-performance laser applications.

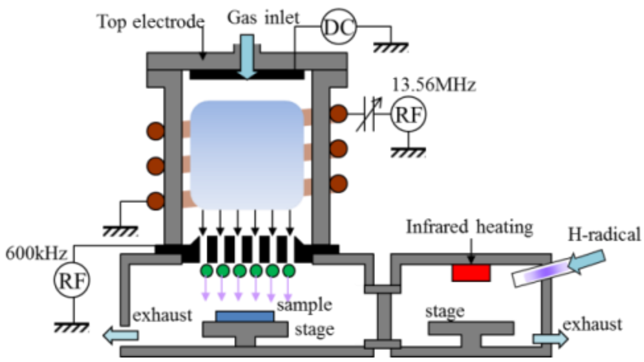

Figure 1. Schematic illustration of NBE system

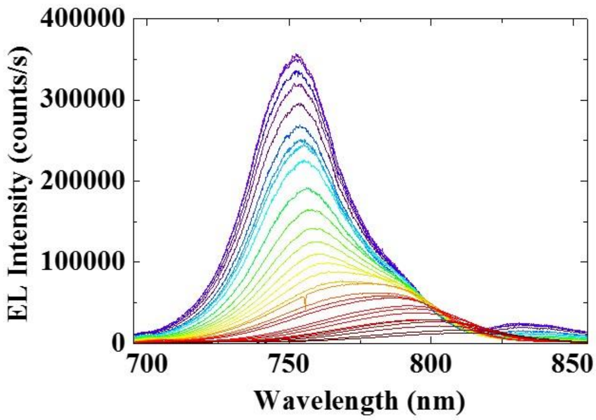

Figure 2. Electroluminescence characteristic of various temperatures of QND-LED from 7K to 300K.

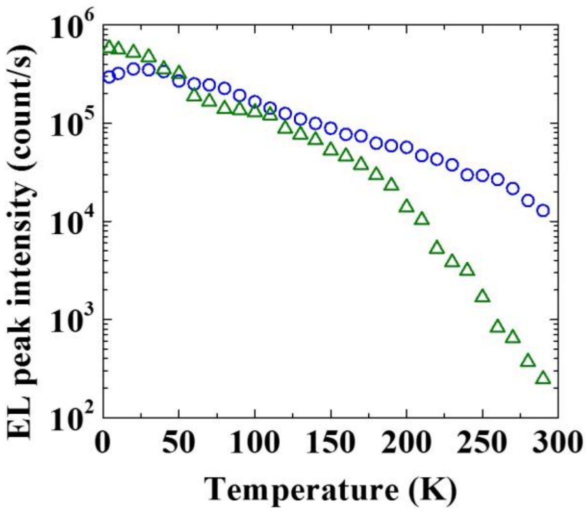

Figure 3. Room temperature operation of GaAs QND-LED Circle: 12nm-thick, triangle: 8nm-thick

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