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High Density and High Aspect Ratio GaAs/AlGaAs Nanopillar array Fabricated by Fusion of Bio-Template and Neutral Beam Etching

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Abstract

III–V compound semiconductor quantum dots (QDs) photonic devices are very attractive because of their many advantages. We developed a defect-free top-down fabrication process for sub-20-nm-diameter GaAs quantum nanodisks (NDs)by using a bio-template and neutral beam etching (NBE). We successfully fabricated 100-nm-high nanopillars embedded in 8-nm-thick GaAs and 30-nm-thick $Al_{0.3}Ga_{0.7}As$ barrier-stacked structures. The GaAs capping layer and $Al_{0.3}Ga_{0.7}As$ barrier layer were regrown by metalorganic vapor phase epitaxy (MOVPE). We measured the photoluminescence (PL) originating from the GaAs NDs at 6 K. To realize NDs laser diodes by top-down fabrication is a great challenge.

1. Introduction

QDs as laser gain media have generated 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 potential applications in telecommunication technology and information technology for III-V compound semiconductor photonic devices, 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 NDs 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 high aspect ratio nanopillars that include GaAs NDs by etching a GaAs/AlGaAs stacked-layered structures, which were fabricated by MOVPE, using a bio-template and NBE. We clearly observed PL from the GaAs NDs after using MOVPE to regrow the samples.

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. Single quantum wells (QWs) with an 8-nm thickness were grown by MOVPE on semi-insulating GaAs substrates. The structure consisted of a 232-nm-thick GaAs buffer layer, an 8-nm-thick undoped GaAs single QW, clad on either side with barrier layers of 30-nm-thick $Al_{0.3}Ga_{0.7}As$, and a 5-nm cap of undoped GaAs. First, hydrogen-radical treatment was used to remove the native oxide on the GaAs cap surface. Second, the sample was transferred under vacuum to the neutral beam oxidation (NBO) chamber, and a thin GaAs-NBO film was sequentially formed at room temperature with oxygen. Then, the 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 or cobalt oxide cores, to make the distance between ferritins greater than 30 nm to eliminate the coupling of wave functions between GaAs NDs. Then, oxygen-radical treatment was used to remove the ferritin protein shell at room temperature with oxygen. The remaining 7-nm diameter iron or cobalt 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, the $Al_{0.3}Ga_{0.7}As$ barrier and GaAs cap were regrown by annealing the sample at 700 °C and 610 °C, respectively. MOVPE was used to fill the gaps between nanopillars.

3. Results and Discussion

Figure 2 shows a scanning electron microscopy (SEM) image of the as-etched samples. We successfully fabricated high aspect ratio sub-20-nm-diameter nanopillars by chlorine NBE, as shown in Fig. 1. Also a scanning transmission electron microscopy (STEM) image of AlGaAs nanopillars is shown in Fig. 2. We could see that gaps between GaAs/AlGaAs nanopillars were filled by MOVPE. We measured the photo-excited emission from 8-nm-thick GaAs NDs, as shown in Fig. 3(a). Emissions from 8-nm-thick GaAs QW were observed at 797 nm, and the full width half of maximum (FWHM) was 18 nm. In contrast, strong PL bands centered at 739 nm were observed for the 8-nm-thick GaAs NDs with FWHM of 57 nm. These observed peaks in the PL spectra were clearly distinguished from those of the GaAs QWs. The emission energy of the NDs sample was blue-shifted by 58 nm compared with that of the 8-nm-thick GaAs QWs. Figure 3(b) shows the time decay of the NDs sample emission at 739 nm. The decay time is 350 picoseconds. The decay time shows the same order of the referenced GaAs QW. This means the fabricated GaAs NDs are defect-free structures. Therefore, the fabricated NDs have great potential for realizing quantum level optoelectronic devices with controllable diameter and thickness.

4. Summary

We observed 8-nm-thick GaAs NDs PL spectra 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 30 nm) by using PEG ferritin, NBE, and MOVPE regrowth. The strong PL emission shows that these fabricated NDs have immense potential for use in high-performance laser applications.

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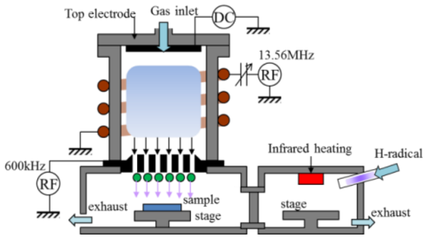
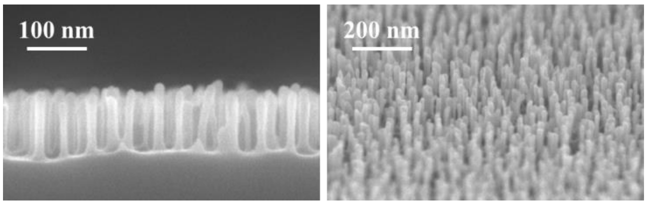
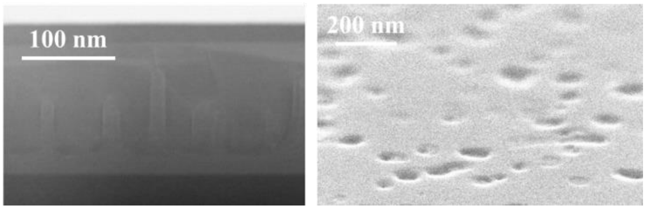


Figure 1. Schematic illustration of the neutral beam etching system



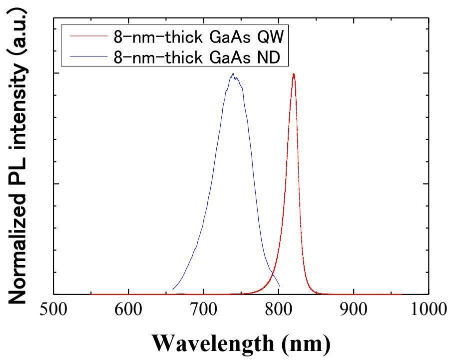
(a) (b)

Figure 2. SEM images after neutral beam etching, (a) cross section, (b) tilt 20°.

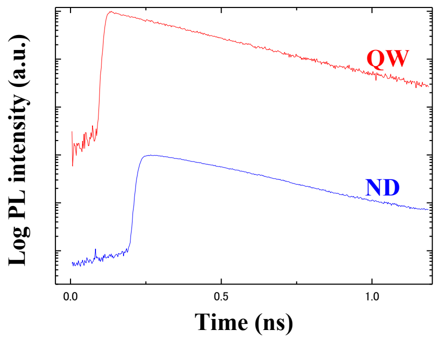


(a) (b)

Figure 3. After regrowth by MOVPE (a) cross sectional STEM images, (b) SEM images of the sample surface from tilt 20°.



(a)



(b)

Figure 3. PL spectra and decay time of 8-nm-thick GaAs nanodisks, (a) PL spectra of 8-nm-thick GaAs ND and QW, (b) PL decay time of 8-nm-thick GaAs ND and QW.