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Room temperature observation of optical modes in transferred rolled-up InGaAs/GaAs quantum dot microtube with AlGaAs confining layers

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ABSTRACT

We realized the excellent confinement of carriers in single-layer InAs quantum dots (QDs) via introducing two AlGaAs confining layers (CLs), and then fabricated the corresponding rolled-up InGaAs/GaAs QD microtubes by conventional photolithography and wet-etching. Subsequently, the as-fabricated AlGaAs confined QD microtubes were transferred to a Si-based SiO_x substrate using a simple liquid-assisted substrate-on-substrate transfer process, thus obtaining the microtube ring resonators. Through micro-photoluminescence (μPL) measurement, optical modes were observed at room temperature and a maximum Q-factor of ~ 550 was demonstrated. In order to clearly show the effect of AlGaAs CLs, we also fabricated and transferred QD microtubes without AlGaAs CLs for comparison. μPL spectra collected at 80 K confirmed that the PL intensity of the central optical mode was increased ~ 10 times with the assistance of AlGaAs CLs. We have confidence that QD microtube ring resonators can be further improved through the incorporation of double-layer QDs together with AlGaAs CLs.

1. Introduction

Rolled-up III-V semiconductor microtubes have sparked great attentions and been widely used in photonic integrated circuits [1], optoelectronics [2], microfluidics [3] and so on, due to the elegant fabrication procedures, the epitaxially-smooth tube wall and the potential to be integrated with on-chip system [4,5]. Particularly, as self-organized quantum dots (QDs) have the unique three-dimensional carrier confinement property and a delta-function-like density of states (DOS) [6–9], the III-V semiconductor microtubes with QDs embedded into the tube wall attract great interest and become a new research hotspot nowadays. A diverse range of applications using the emerging QD microtubes have been demonstrated, including optically-pumped lasers [10], photodetectors [11], photo transceivers [12], directional couplers [13] and so on.

Observing optical modes in III-V semiconductor QD microtubes is of critical significance for realizing microtube devices including lasers [14], sensors [15], lab-in-a-tube system [16], etc. Li et al. have realized the first room temperature InGaAs/GaAs QD microtube optical ring resonator in 2009 [17]. After that, some works about the InGaAs/GaAs QD microtubes functioning as optical ring resonators at room temperature have been reported experimentally. In addition, some specially shaped lobes were designed and fabricated along the rolling edge of double-layer QD microtubes, and therefore axial modes were observed and simultaneously Q-factor was enhanced from ~ 350 (without any lobe) to ~ 2000 [18]. Optically-pumped lasing from InGaAs/GaAs QD microtubes [19] and integrating QD microtubes with waveguides [4] were also realized. However, to the best of our knowledge, all the aforementioned reports were based on the incorporation of double-layer stacked InGaAs QDs into the tube wall. While in the stacked QD heterostructure, due to the adoption of thin GaAs spacing layer (~ 10 nm), upper layer QDs are much more easily relaxed, further making the stack of multi-layer QDs difficult.

Therefore, in this study, we introduced two AlGaAs confining layers (CLs) to sandwich the single-layer InAs QDs gain region, not only avoiding the disadvantage of the multi-stacked QDs in microtube, but also realizing a better confinement of the carries and suppressing the losses induced by the nonradiative surface recombination. Benefiting from our previous experience in quantum well microtube (i.e., there were no optical modes observed from the single quantum well

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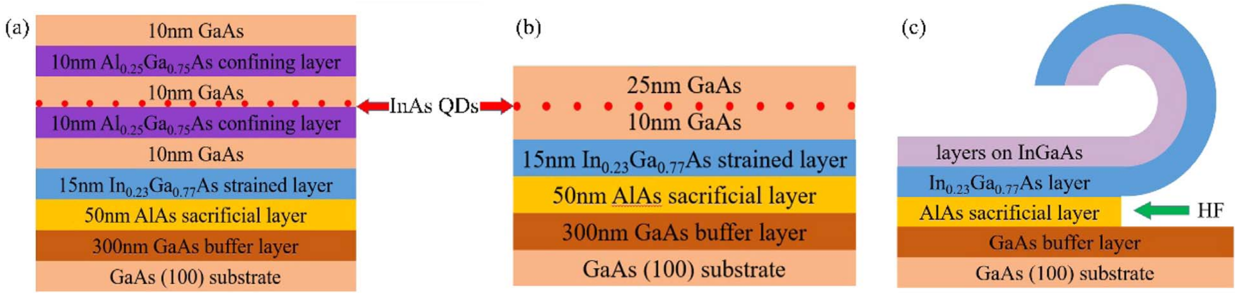

Fig. 1. (a-b) Planar heterostructures of the QD microtubes with and without AlGaAs CLs. All the heterostructures were grown on GaAs (100) substrates by MBE. (c) Schematic illustration of the self-rolling process.

microtube because of the insufficient separation of ~ 100 nm between the GaAs wafer and the microtube as well as the resulting severe light leakage) [20], we transferred the rolled-up InGaAs/GaAs QD microtubes from the host GaAs wafer to a low-refractive-index Si-based SiO_x substrate, and finally observed the optical modes at room temperature. Additionally, in order to verify the effect of AlGaAs CLs, we also fabricated and transferred QD microtubes without AlGaAs CLs to compare with their AlGaAs confined counterparts. μPL spectra collected at 80 K clearly showed that the central optical mode was enhanced approximately one order of magnitude after the introduction of two AlGaAs CLs.

2. Experimental

The AlGaAs confined QD microtube heterostructure was grown on a GaAs (100) substrate by solid source molecular beam epitaxy (MBE). As illustrated in Fig. 1(a), a 300 nm-thick GaAs buffer layer was first grown, followed by a 50 nm-thick AlAs sacrificial layer, a 15 nm-thick $In_{0.23}Ga_{0.77}As$ strain-driving layer and a 10 nm-thick GaAs layer. Subsequently, a 10 nm-thick GaAs layer sandwiched by 10 nm-thick lower and upper $Al_{0.25}Ga_{0.75}As$ CLs was grown, in which a single-layer of InAs QDs (~ 2.6 ML) was deposited and then immediately capped by GaAs. Finally, a 10 nm-thick GaAs protective layer was grown to suppress the oxidation of AlGaAs. The QD microtube heterostructure without AlGaAs CLs was also grown, as shown in Fig. 1(b).

For the fabrication of QD microtubes on the GaAs wafer, rectangular patterns (size: 180 μm × 30 μm for the microtubes with AlGaAs CLs, 180 μm × 20 μm for the microtubes without AlGaAs CLs) along the [001] direction were first defined and then transferred to the wafer by photolithography. Next, the mesas were obtained through a shallow etch to the AlAs sacrificial layer by H_2SO_4:H_2O_2:H_2O (1:1:60) solution. Finally, as shown in Fig. 1(c), the AlAs sacrificial layer was laterally etched away by highly-selective HF:H_2O (1:40) solution, which made the mesas gradually roll up from their long-sides and finally form the microtubes on the GaAs wafer due to the strain relaxation [21]. After the rolling-up process, the short-sides of the mesas became the circumferences of the microtubes.

After the fabrication of microtubes, ethyl alcohol solution was dropped onto a Si-based 300 nm-thick SiO_x substrate and then the as-obtained GaAs-based QD microtube wafer was directly flipped on the top of the SiO_x substrate, realizing a face-to-face contact between two wafers (The SiO_x substrate was placed at the bottom). The QD microtubes were released from the GaAs wafer by ethyl alcohol and then dropped onto the SiO_x substrate due to the gravity. After drying up in the air, the QD microtubes stuck to the SiO_x substrate via Van der Waals force when the GaAs wafer was removed, and the QD microtubes were successfully transferred from the host GaAs wafer to the SiO_x substrate [22]. The QD microtubes without AlGaAs CLs were also fabricated and transferred to a SiO_x substrate through the same process.

Scanning electron microscopy (SEM) measurements were carried out to characterize the morphologies of microtubes. Micro-photoluminescence (μPL) spectra were collected at room temperature and low temperature (80 K) to investigate the optical properties of QD microtubes. A 532 nm laser was used for excitation and the acquisition time was fixed to 10 s. At room temperature the laser beam was focused on the sample by a 100 × objective lens (N.A. = 0.85), resulting in a spot size of ~ 3 μm in diameter. The laser power was ~ 50 μW. As the microtube samples had to be mounted in a continuous-flow cryostat during the low temperature measurement, a 50 × objective lens (N.A. = 0.5) was used for the focus. Corresponding spot size was ~ 4 μm and the laser power was ~ 60 μW. The emission through the microscope objective was detected by a silicon charge-coupled device (CCD).

3. Results and discussion

The SEM image of a 180 μm long AlGaAs confined QD microtube transferred to a SiO_x substrate is shown in Fig. 2(a). As shown, the diameter of the microtube is quite uniform along the axial direction and the outer wall surface of the microtube is smooth and crackless, manifesting the excellent structural properties. The magnified SEM image of the transferred microtube is shown in Fig. 2(b). The outer diameter of the microtube is ~ 7.5 μm and the microtube is ~ 1.3 revolutions according to the size of the mesa.

Room-temperature μPL spectra of the AlGaAs confined QD microtube on SiO_x, on GaAs and corresponding as-grown planar heterostructure are shown in Fig. 3(a), in which the PL intensity of InGaAs

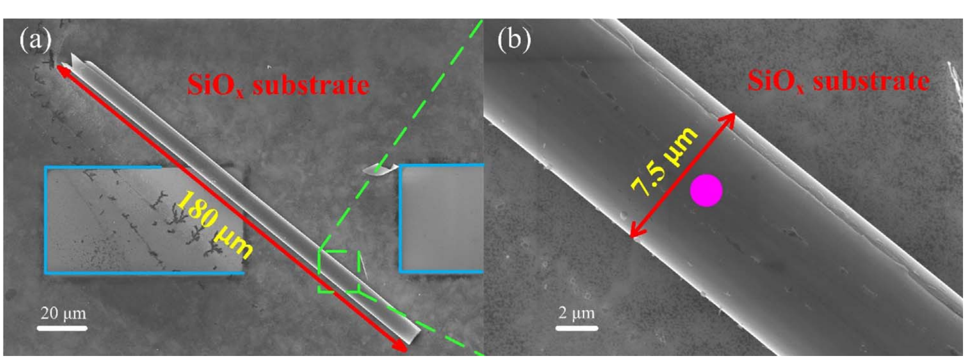

Fig. 2. (a) The SEM image of a 180 μm long AlGaAs confined QD microtube transferred to a Si-based SiO_x substrate. The rectangular patterns marked by blue lines on the SiO_x substrate were originally used to determine the position of the transferred microtube. (b) The magnified SEM image of the microtube with ~ 7.5 μm outer diameter and ~ 1.3 revolutions. The PL spectrum shown in Fig. 3(b) was measured from the pink point.