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Optical Characteristics of Two-Dimensional Photonic Crystal Slab Nanocavities with Self-Assembled InAs Quantum Dots Emitting at Over 1.3-μm

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1. Introduction

Thin slab nanocavities with a single defect in two-dimensional (2D) photonic crystals have attracted much attention because of the prospect of high quality factors (Q) with extremely small volume. Several groups have so far achieved the lasing action using the defect mode of photonic crystals [1]. Recently, quantum dots (QDs) are promising as the light source of the photonic crystal slab nanocavities since the surface recombination loss is expected to be small due to the reduction of carrier diffusion in the QDs plane [2,3]. In addition, QDs are expected to improve the laser characteristics such as the threshold current density and temperature sensitivity if used as the active layer of semiconductor lasers, owing to reduction of the dimensionality of the electron motions in quantum nano-structures [4]. Recently, it is also of great interest that QDs will be useful for the application to the GaAs-based optical devices at the wavelength of 1.3 or 1.55-μm suitable for fiber-optic communication systems. Many groups reported the continuous-wave (cw) lasing at 1.3-μm using In(Ga)As QDs as the active layer [5]. We achieved the 1.52-μm luminescence from InAs QDs embedded in InGaAs strain-reducing layer at room-temperature (RT) [6].

In this paper, we report the fabrication and the optical characteristics of 2D photonic crystal slab nanocavities with self-assembled InAs QDs emitting at over 1.3-μm. We observed the enhanced luminescence and sharp peaks at the wavelength of near 1.3-μm that originated from the defect modes of 2D photonic crystal slab.

2. Experiments

The sample was grown by low-pressure metalorganic chemical vapor deposition at the total pressure of 76 torr. The active layer consists of two layers of InAs QDs separated by 20-nm of GaAs. The QDs active layers are embedded in 300-nm of GaAs. The height, diameter and density of InAs QDs were 7, 20 nm, and 2.0×10^{10} /cm^2, respectively [5]. 500-nm of AlAs sacrificial layer was inserted below the active layer. Photonic crystal patterns with a single defect were formed by using electron-beam lithography and inductively-coupled-plasma reactive ion etching with Cl_2/Xe. Then we fabricated the air-bridge structure by removing AlAs sacrificial layer using the wet chemical etching process with buffered hydrofuluoric acid (Fig. 1).

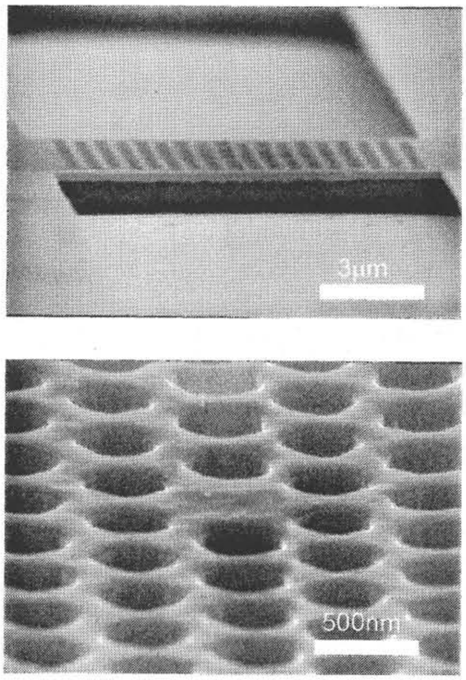

Fig. 1 Scanning Electron Microscopic images of 2D photonic crystal slab nanocavity with a single defect. The single defect is at the center of the photonic crystal slab structure. The thickness of photonic crystal slab is 300 nm.

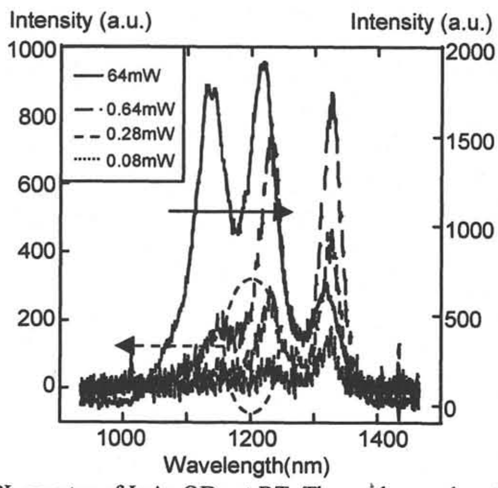

Fig. 2 PL spectra of InAs QDs at RT. The peak wavelength of the ground and excited states are 1.32, 1.22, and 1.13-μm, respectively. FWHM of the ground state is 23 meV.

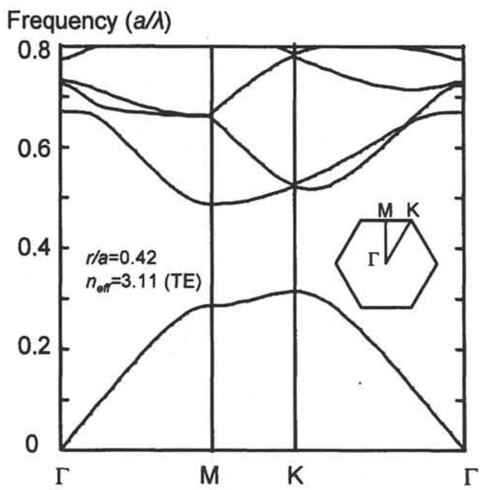

Fig. 3 Photonic band diagram for TE-like mode along two symmetry direction by 2D FDTD method. The refractive index (*neff*) is 3.11 for TE-like mode.

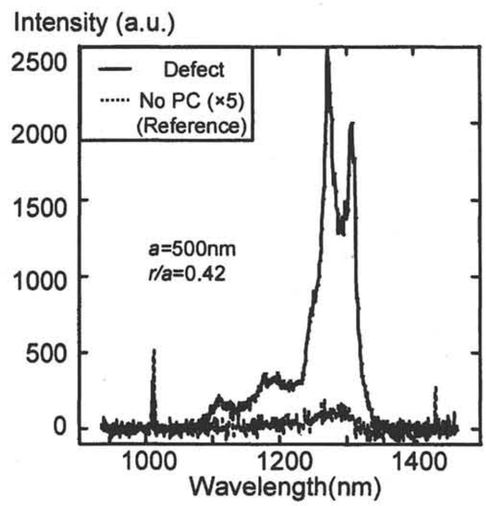

Fig. 4 PL spectra of a single defect of photonic crystal slab nanocavities and the reference (without photonic crystals (PC)) at the same excitation power. Compared with the reference, the luminescence from InAs QDs is strongly enhanced at a single defect of 2D photonic crystal slab. Moreover, two sharp peaks are also observed at the wavelength of 1.27 and 1.31-μm.

We measured the photoluminescence (PL) of InAs QDs at RT using InGaAs liquid-nitrogen-cooled charge-coupled device detector with the excitation by Ti:Sapphire laser (cw) at the wavelength of 840 nm. The PL spectra of InAs QDs at various excitation powers are shown in Fig. 2. At lower excitation power, only the ground state of QDs was observed. However, with increasing the excitation power, the luminescence from the ground and excited states of QDs was observed at 1.32, 1.22 and 1.13-μm.

Next, we investigated the optical characteristics of 2D photonic crystal slab nanocavities with QDs. The lattice constant (a) was 500 nm and hole radius (r) was 210 nm. First, we calculated the photonic band diagram and defect modes corresponding to our samples by 2D finite-difference time-domain (FDTD) method. The photonic band diagram for transverse-electric-like (TE-like) mode is shown in Fig. 3 (n_{eff}=3.11 for TE). We estimated the normalized frequency (a/λ) of defect modes to be approximately 0.324, 0.408, 0.428 and 0.456. Then we measured the luminescence from a single defect using conventional micro-PL system. PL was collected from the top of a sample using a ×100 microscope objective lens. The PL spectra of a single defect of 2D photonic crystal slab and the reference (i.e. the sample without photonic crystals) are shown in Fig. 4. Compared with the reference, the luminescence from InAs QDs was strongly enhanced at a single defect of 2D photonic crystal slab. Moreover, two sharp peaks were also observed at the wavelength of 1.27 and 1.31-μm. We confirmed that these peaks originated from the defect modes within the single defect of 2D photonic crystal slab.

3. Conclusions

We reported the fabrication and the optical characteristics of 2D photonic crystal slab nanocavities with a single defect containing self-assembled InAs QDs emitting at over 1.3-μm. We observed the enhanced luminescence and sharp peaks at a single defect that originated from the defect modes of 2D photonic crystal slab.

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