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Observation of Light Emission at ~1.5 μm from InAs Quantum Dots in Photonic Crystal Microcavity

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1. Introduction

Semiconductor quantum dots (QDs)[1] have many important properties for applications to optoelectronic and nanophotonic devices because of their quasi-atomic nature in electron density of states. Recently, quantum optical and quantum information devices using QDs such as single photon emitters[2,3] have attracted much attention. For development of these devices, design and fabrication of photonic cavity possessing high quality factor (Q) with small mode volume (V) are important for enhancing the interaction of QDs with a cavity mode. Photonic crystal (PhC) microcavities are promising cavity structures for these applications because very high Q/V, which is an important figure of merit for the cavity quantum electrodynamics phenomena, can be achieved[4].

So far, PhC microcavities containing QDs have been studied by several groups[5-8]. Important results such as an enhancement of spontaneous emission of QDs[7] and lasing action with a low threshold pumping power[8] have been reported. However, the emission wavelengths of QDs in these studies are around 1.3 μm or shorter (less than 1 μm). For the applications of QD-PhC systems as high efficient single photon emitters, emission wavelength of ~1.5μm is desirable because this spectral range is suitable for long-distance, fiber-based applications. Very recently, InAs QDs on InP were introduced into a micro-post cavity and resonant peaks have been observed[9]. PhC microcavities are more promising structures because a larger Q/V can be achieved compared to that in the micro-post cavities.

In this paper, we report the first experimental demonstration of light emission at ~1.5 μm from InAs QDs coupled with PhC microcavity modes. An emission linewidth of ~1.7 nm, which corresponds to a cavity quality factor of ~900, was obtained.

2. Fabrication of PhC microcavity with QDs

Samples were grown by metal organic chemical vapor deposition (MOCVD) on a GaAs substrate. At first, a 500 nm thick AlGaAs was deposited as a sacrificial layer to form air-bridge structure. Then, a 240 nm thick GaAs slab layer was grown. In the middle of the GaAs layer, we introduced a single layer of InAs quantum dots capped with InGaAs strain-reducing layer (SRL) and GaAs layer. The QD density is ~1.5×10^{10} cm^{-2}. The growth conditions for QDs and SRL are crucial for achieving emission around 1.5 μm with a narrow linewidth[10]. Recent development of the growth technology for QDs emitting around 1.5 μm will be reported elsewhere[11]. The photoluminessence (PL) spectrum for as grown structure is shown in Fig. 1. Clear QD emission peak was observed at ~1.5 μm.

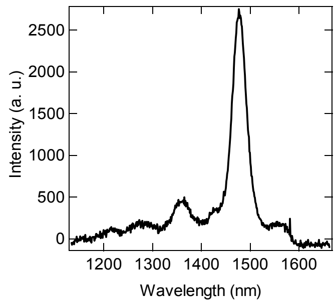

Fig.1 PL spectrum for as-grown InAs QDs embedded in GaAs slab structure. He-Ne laser is used as an excitation light source.

We improved the fabrication processes for PhC slab structures compared to that in our previous work[5]. This enables us to fabricate PhC microcavities more precisely. A 100 nm thick SiO_2 layer was sputtered onto the sample surface, and then a 200 nm thick e-beam resist was coated. Hexagonal PhC patterns with a point defect consisting of seven missing air holes (H2 defect) were patterned into the resist by electron beam lithography. These PhC patterns were transferred into the SiO_2 layer by C_4F_8-based inductively coupled plasma (ICP) etching. This SIO_2 layer was used as a mask when we etched air holes into GaAs and AlGaAs layers by Cl_2-based ICP etching. Figure 2 shows (a) top and (b) cross-sectional scanning electron

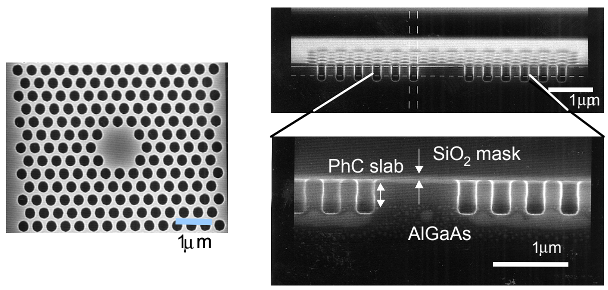

Fig. 2. SEM images of a H2 cavity structure studied here. (a)Top, (b)cross-sectional, and (c)magnified cross-sectional images.

microscope (SEM) images of a H2 defect structure just after Cl_2-based etchig. In the magnified view (c), a residual SiO_2 mask is seen on the GaAs surface. The sidewall angle is more than 85 degree. Finally, AlGaAs sacrificial layer and residual SiO_2 mask were etched away by 10% HF solution in order to form air-cladding layers below and above the GaAs slab.

3. Optical characterization

Fabricated structures were characterized by using μ-PL measurements at room temperature. Figure 3 shows μ-PL spectra from QDs in H2 cavities with different PhC structural parameters. CW Ti:sapphire laser (λ=780 nm, P=100 μW) was focused onto the sample surface through an objective lens (x50, NA=0.45) and PL from QDs were collected through the same lens. Several sharp peaks are observed and shift systematically depending on the structural design parameters. These peaks correspond to the cavity modes of a H2 cavity. The resonant wavelengths obtained by the three-dimensional finite difference time domain (3D-FDTD) calculation are also shown. Good agreement is found between the experimental results and the FDTD calculation. PL signal from QDs in PhC microavity is largely enhanced. The PL intensity upon

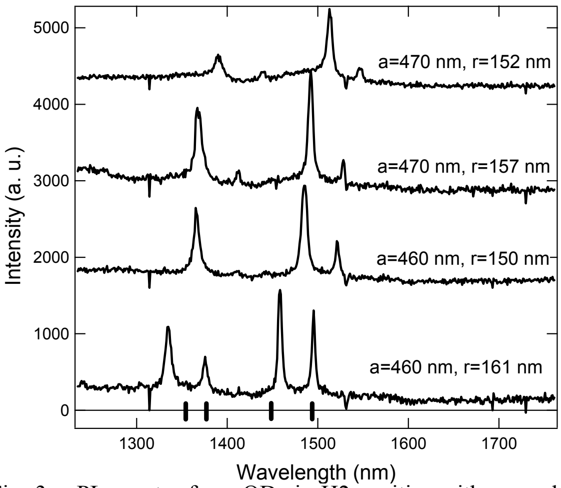

Fig. 3 μ-PL spectra from QDs in H2 cavities with several different structural parameters. Black bars on the zero line shows resonant wavelengths obtained by FDTD calculation.

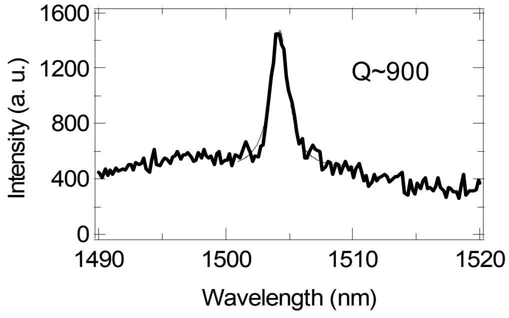

Fig. 4 High-resolution μ-PL spectrum for a H2 cavity with a=460 nm and r=138 nm.

the PhC cavity is more than 100 times higher than that without PhC structure.

An emission linewidth of ~1.7 nm was estimated from high-resolution μ-PL measurements (see Fig. 4). This linewidth corresponds to the cavity quality factor of ~900. This is higher value than that obtained in the micro post cavity with a post radius of 1μm[9], which is similar to the lateral size of H2 cavity studied here.

4. Conclusions

We have fabricated PhC microcavities with InAs QDs and have demonstrated the coupling of QD emission at ~1.5 μm to the PhC microcavity modes for the first time. A cavity quality factor as high as ~900 was obtained. This value can be increased by carefully designing the cavity structure. This result is an important step for applications of QD-PhC systems as single photon light sources at the optical communication wavelength.

Acknowledgements

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