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Light emission from a strongly coupled single quantum dot-photonic crystal nanobeam cavity system

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1. Introduction

Coupling between excitons in single semiconductor quantum dots (QDs) and photons in high-Q small cavities has receiving much attention because of its potential applications to novel optoelectronic and quantum information devices, in addition to its scientific interests. Light-matter coupling in such cavities is dramatically modified due to the cavity quantum electrodynamics (CQED) effects. Since the first demonstrations of the strong coupling phenomena between a QD exciton and a single photon in a micropillar [1] and a photonic crystal (PhC) cavity [2], several groups including us have reported interesting works in this field [3,4,5]. Among several kinds of photonic micro/nano cavities, PhC nanocavities have preferable features for CQED in solid state, that is, high Q factor and small mode volume. So far, two-dimensional (2D) PhC cavities are widely used for such experiments. However, in order to maintaining high Q that enough for observing strong coupling, large number of surrounding air holes around the cavity are required, which results in larger actual device size. Recently, ultrahigh Q ($>10^8$) nanocavities based on one-dimensional configuration, so called, PhC nanobeam cavity has been proposed [6] and been experimentally investigated [7,8]. In PhC nanobeam cavity structures, air holes vertical to the beam can be omitted and it can reduce the footprint of the solid-state CQED devices. This smaller physical size would be useful for densely integrated quantum devices. In addition, the small device size means the light weight, which would open a way to the new paradigm in CQED through the interaction with mechanical vibration.

In this paper, we report on the first observation of strong coupling phenomena between a single QD coupled with a PhC nanobeme cavity. The measured cavity decay rate κ and the estimated coupling constants g are 109 μeV, ~32 μeV, respectively. The criteria for the strong coupling regime $g > \kappa/4$ is satisfied.

2. Sample design and fabrication

Our cavity structure is schematically illustrated in Fig. 1(a). The cavity is located at the center part of 46 circular air holes that are introduced into a one-dimensional nanobeam with a width w of 375 nm and a height h of 130 nm. The period of the air hole a is 250 nm and the radius r is 77 nm except for the air holes at the middle part. The cavity design is similar to that of reference 9. The distances to the adjacent air holes around the cavity center (see Fig. 1 (a)) are modulated from the center to the edge. The values of a_1, a_2, a_3, a_4, a_5, and a_6 are 210, 211, 214, 220, 228, and 238 nm, respectively. The fundamental cavity mode is found at the wavelength of 1025 nm in the FDTD calculation. The calculated Q approaches up to 10^5 with a cavity mode volume of $0.71(\lambda/n)^3$, which are enough for bringing the system into the strong coupling regime.

We fabricated the designed structure using conventional fabrication processes for 2D PhC cavities. First, a 130-nm-thick GaAs slab is grown by MBE on a GaAs substrate with a 1-μm–thick AlGaAs sacrificial layer. At the middle of the slab, a self-assembled InGaAs QD layer is inserted. The areal density of QDs is approximately 5×10^8 cm^{-2} and the QD ensemble forms the peak emission wavelength at 980 nm at 4K. Details of the growth condition have been reported in reference 10. After the growth, the nanobeam cavity structure is patterned by using e-beam lithography and dry etching techniques. A typical SEM image of 1D cavity is shown in Fig. 1(b).

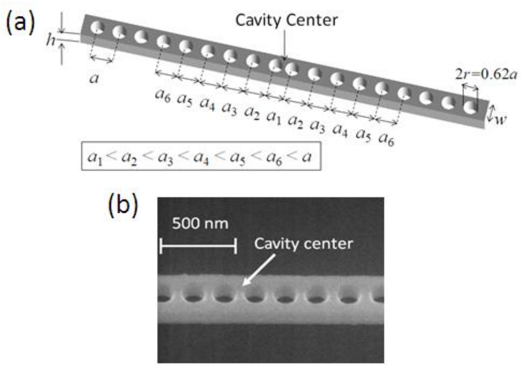

Fig. 1: Schematic (a) and SEM image (b) of the nanobeam cavity.

3. Experimental results and discussions

The sample was characterized by measuring μ-PL at low temperature (6 K). A continuous-wave Ti:sapphire laser operated at the wavelength of 838 nm was used as an excitation source. Photons at this wavelength excite carriers mainly into the GaAs slab. An objective lens (x40, NA0.6) was used to focus the excitation beam and collect the emission. In the present sample, cavity Q was 11,500. Although, this value is much smaller than the Q factor predicted by the FDTD calculation, it is already comparable to 2D active PhC cavities operating below 1 μm and is enough to achieve the strong coupling. The discrepancy between theoretical and actual Q values is mainly attributed to the imperfections in the fabrication processes.

We investigated the coupling between a single InGaAs QD and the nanobeam cavity mode by measuring the PL spectra for various detunings between the QD-like emission and the cavity-like emission. A xenon gas deposition technique was used to shift the cavity wavelength across the QD exciton line. Fig. 2(a) summarizes the results. Around the exact resonance condition between the QD and the cavity, two peaks shift repulsively. The shape of the PL spectrum at the resonant condition is not a single Lorentzian but a flat-top structure as shown in Fig. 2(b). This is a signature of the strong coupling. By fitting the series of spectra, we extracted the peak wavelengths of the two modes (see Fig, 2(c)) and coupling constant g of ~ 32 μeV between the exciton and the cavity photon. Here, we used measured Q of 11,500, corresponding to κ = 109 μeV. The obtained g and κ actually satisfy the strong coupling condition, which is described by the following inequality.

$$g > \kappa/4 \qquad (1)$$

Here, the effect of the line broadening of QD emission is neglected because the cavity linewidth is much wider than that of the QD.

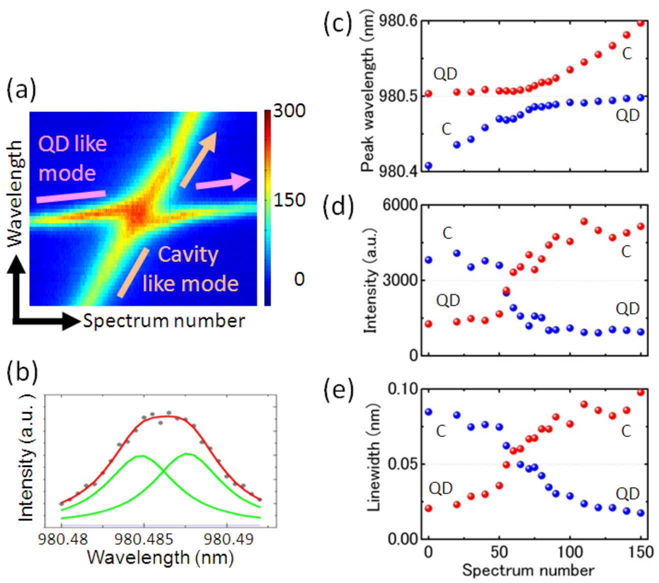

Fig. 2: (a) Color map for the PL spectra for various detunings, (b) PL spectrum at the resonance. The red curve is the result fitted to the data by using two Lorentz functions (green curves) (c-e) Change of the peak positions, integrated intensities, and linewidths for the QD-like (QD) and cavity-like (C) modes. Red and blue circles denote the measured behaviors of the lower and upper polariton branches, respectively. The horizontal axis indicates the spectrum number, corresponding to the detuning between the QD-like and cavity-like modes.

The changes of the peak intensities and linewidths give us more fruitful information on the light-matter coupling around the resonance. The transitions of the integrated intensities and the linewidths of the QD and the cavity in the cavity scanning measurement are shown in Fig. 2 (d) and (e), respectively. Linewidth and intensity mixing are clearly observed around at the resonance. These are expected behaviors in the strongly coupled system.

4. Conclusion

We observed light emission from a single InGaAs QDs coupled with a 1D PhC nanobeam cavity mode. The results shows that the QD is strongly coupled with the 1D PhC cavity mode with a coupling constant of 32 μeV. This is the first observation of the strong coupling phenomena in 1D PhC nanocavity with a single QD. By optimizing the fabrication processes, the cavity Q could be largely improved. Moreover, stronger QD-cavity coupling could be achievable by utilizing a higher order cavity mode with a smaller mode volume of about 0.3 $(\lambda/n)^3$. The strongly coupled QD-PhC nanobeam cavity system presented here will pave a way for accessing the interesting physics and quantum devices with a truly small size.

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