Photonic crystal microcavities for cavity quantum electrodynamics

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ABSTRACT

We have measured quality factors as high as 4000 for cavity resonances at 1.3 eV in photonic crystal microcavities formed by removing seven holes. In this paper, we discuss the prospect of coupling a single optical mode of a photonic crystal microcavity to the single-exciton (1X) level of a semiconductor quantum dot.

Keywords: photonic crystal, microcavity, cavity quantum, quantum dot

1. INTRODUCTION

Purcell was first to recognize that if an emitter is placed inside a high quality (Q) cavity then its spontaneous emission rate will differ from its value in vacuum.[1] Depending on the coupling strength, the spontaneous emission can be enhanced (weak coupling) or be made reversible (strong coupling). In the strong coupling regime, the cavity dynamics are described by vacuum-field Rabi oscillations. Weak coupling would allow novel optical devices such as single-mode light-emitting diodes and single photon sources that can operate at higher frequency.[2,3] Strong coupling would allow all-optical quantum computing using quantum dots.[4]

While strong coupling has been observed for atoms in optical cavities formed by spherical mirrors,[5] exciton-photon strong coupling has not yet been observed in semiconductor microcavities using quantum dots due to requirements which are challenging even for modern techniques in semiconductor nanofabrication. The best results to date have been in microdisk cavity resonators[6,7] with Q factors of up to 12000 for 2 μm disks. We have recently measured an enhancement of the spontaneous emission rate by a factor of 6 for a quantum dot in microdisk cavity.[8]

Recent work in photonic crystal microcavities has resulted in coupling performance approaching that of the best microdisks with several additional advantages. Cavities formed from photonic crystals are capable of much smaller mode volumes than microdisks (up to 25 times smaller) due to their improved in-plane confinement, and this smaller mode volume somewhat relaxes the requirement for high Q. The scalability of Maxwell's equations allows cavity resonances to be easily tuned by changing the lattice constant prior to fabrication. These microcavities also have the benefit that errors introduced during the fabrication process can lift the mode degeneracy while still exhibiting high Q. Recently, we have measured Q factors as high as 4000 for nondegenerate modes at 1.3 eV in photonic crystal microcavities formed by removing seven holes (H2).[9] In this paper, we discuss the prospect of coupling a single optical mode of a photonic crystal microcavity to the single-exciton (1X) level of a semiconductor quantum dot located in the defect of the microcavity (Figure 1).

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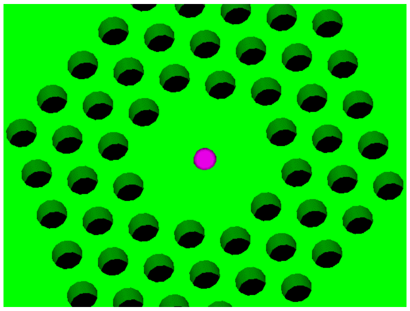

Figure 1: A semiconductor quantum dot located inside a photonic crystal microcavity.

2. SEMICONDUCTOR QUANTUM DOTS

Semiconductor quantum dots (QD) share many basic properties with atomic systems, so it is useful to think of quantum dots as "artificial atoms". These quantum dots are grown using molecular beam epitaxy of InAs on GaAs. After approximately 1.6 monolayers, InAs, islands form due to the lattice mismatch, and then are subsequently capped with GaAs. We use a partially covered island (PCI) technique[10] to shift the ground state energy to 1.25 - 1.3 eV. Typical sizes for PCI QDs are 40-50 nm diameter and 3 nm height. Quantum dots have discrete energy levels as shown by the sharp emission lines in photoluminescence (PL) spectra. Figure 2 shows PL from a single InAs QD for various excitation powers. For high excitation power, the spectra contain two groups of levels called the s-shell and the p-shell (named after the lowest energy levels in the hydrogen atom). The s-shell contains a nondegenerate level called the single-exciton (1X) level, and it is this level that is interesting for coupling applications.

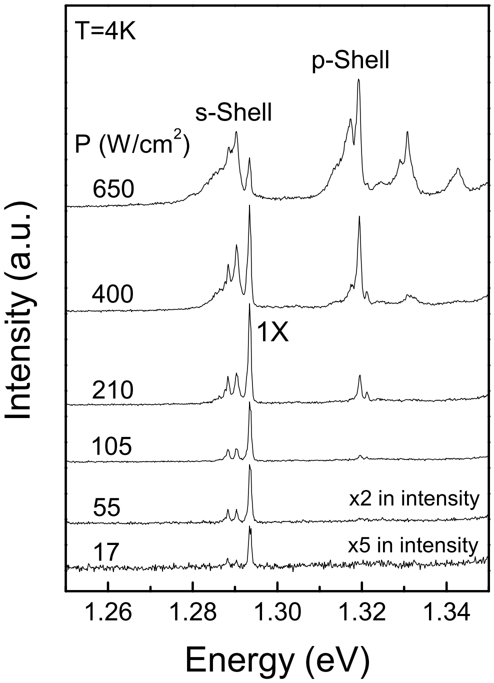

Figure 2. Photoluminescence measurements of a single InAs quantum dot for various excitation powers. The single-exciton (1X) level is of interest for coupling applications.

Since Quantum dots can be grown in a monolithic fashion within the photonic crystal material, the coupling to the cavity does not vary with time. The coherence time of these quantum dots is also believed to be very close to the radiative lifetime, and the oscillator strength was recently shown to be higher than previously expected.[11] These factors allow us to consider using quantum dots in device applications for weak and strong coupling.

3. PHOTONIC CRYSTAL MICROCAVITIES

Photonic crystals are useful for microcavity applications because the photonic band gap creates the possibility of very strong optical confinement. Using the analogy which is often made to electronic crystals, the modes of a resonant photonic crystal cavity can be thought of as defect states which lie inside the photonic band gap. This allows much greater localization of light than the mechanism that gives rise to the modes of microdisk cavity, so cavities formed from photonic crystals are capable of much smaller mode volumes.

In this work, we use two-dimensional photonic crystals since they are easier to fabricate than 3D structures. The photonic crystal microcavities were fabricated by etching a triangular lattice of air holes in a thin GaAs membrane. The fabrication consists of a four-step process which makes use of electron-beam lithography, reactive ion etching, and a chemical wet etch for lift-off, and has been described previously.[9] Figure 3 shows a photonic crystal microcavity formed in a 180 nm GaAs membrane and having a lattice constant of 255 nm. This cavity has a defect formed by removing seven holes.

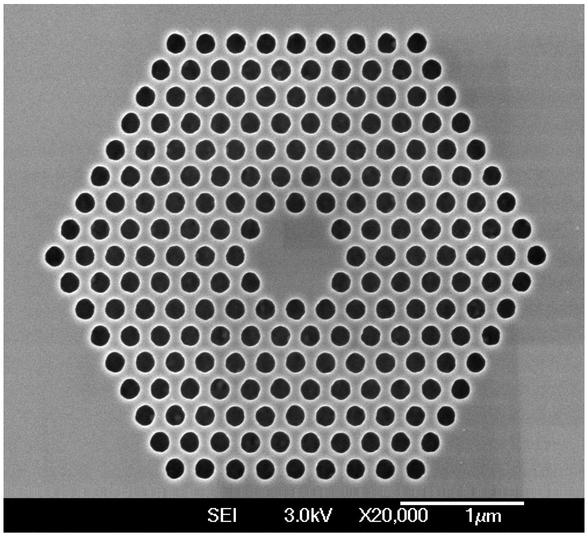

Figure 3. Fabricated photonic crystal microcavity formed by removing 7 holes to create a defect in the shape of a hexagon (H2). The lattice constant is 255 nm.

4. COUPLING REQUIREMENTS AND RESULTS

We now describe the requirements for coupling. This discussion can be applied generally to either weak coupling or strong coupling, the difference between these two regimes being the degree to which the requirements must be satisfied. We also discuss recent progress in each of these areas.

4.1. Figures of Merit

First, we require a significant change to the emitter environment. The cavity should have a mode with high Q and small mode volume. The figure of merit for weak coupling is the Purcell factor which scales as Q/V_{eff}, where the Q is related to the photon lifetime in the cavity, $\tau_p = Q/\omega$, and V_{eff} is the mode volume normalized

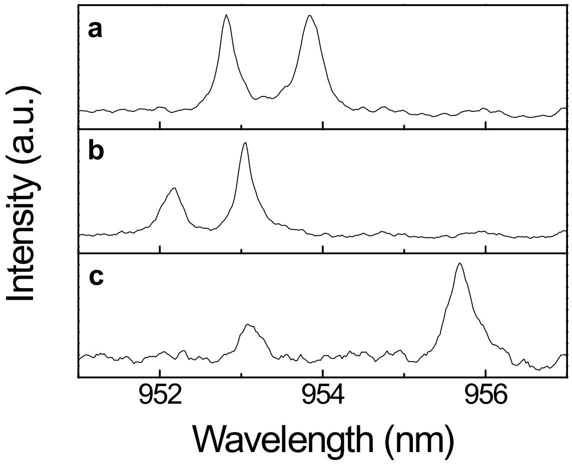

Figure 4. Measured photoluminescence spectra of two high-Q modes for equivalent H2 cavities on the same sample. The Q factors obtained are **a.** 4000 and 3000, **b.** 3000 and 3800, and **c.** 1900 and 2700.

to a cubic wavelength in the emitter environment. While the figure of merit for strong coupling obeys a slightly different scaling law, like the Purcell factor, it also increases for high Q and small mode volume.[12]

Recent progress in photonic crystal microcavites gives Purcell factors competitive with the best results in microdisks. We have recently measured high Q factors for cavity resonances at 1.3 eV in H2 microcavities. We used the inhomogeneously broadened spectrum resulting from a high density of QDs to probe the mode structure of the photonic crystal microcavities. The experimental setup consisted of a low-temperature diffraction-limited optical microscopy for spatially resolved photoluminescence spectroscopy and is described elsewhere.[9] We have measured Q factors as high as 4000 (figure 4) corresponding to a Purcell factor of 150 for these structures.

4.2. Mode Tuning

The second requirement for coupling is that the cavity mode be on spectral resonance with the quantum dot energy. The typical range of energies for the 1X level in InAs quantum dots corresponds to emission wavelengths between 900 and 1000 nm. In order to obtain spectral coupling, the resonant modes of the cavity should be tunable in this wavelength range by the choice of suitable design parameters. From the scalability of Maxwell's equations, we expect that by changing the microcavity dimensions, we will be able to tune the energy of the mode into resonance with a quantum dot. In a photonic crystal, the critical parameters are the hole radius, r, lattice constant, a, and membrane thickness, t. One could also use the index of refraction as a parameter, but typically it is fixed by our choice of starting material. The parameters r, a, and t, can be adjusted to tune the resonances, and the hole radius and lattice constant may even be made to vary over a wide range on a single sample.

Figure 5 shows measurements for H2 defect cavities having lattice constants of 255, 280, and 305 nm. As the lattice constant was increased, the cavity resonance shifted from 893, to 948, to 1002 nm. By varying only the lattice constant we can design microcavity resonances in the desired range. We have estimated the accuracy of mode tuning for the high-Q modes in figure 4. For equivalent cavities, the peak wavelength shifts by up to 3 nm, suggesting the resonance energy for fabricated structures will be within 2 meV of the design target.

4.3. Nondegenerate Modes

For certain applications, one may not care if coupling is to either a single cavity mode or two degenerate modes. However, for this discussion, we only consider coupling to a single nondegenerate cavity mode, since certain applications (i.e. quantum computing) strictly require it. If the microcavity contains symmetry degenerate eigenmodes, this degeneracy must be lifted. In photonic crystal microcavities, certain modes are doubly degenerate due to symmetry. However, these microcavities have the benefit that errors introduced during the

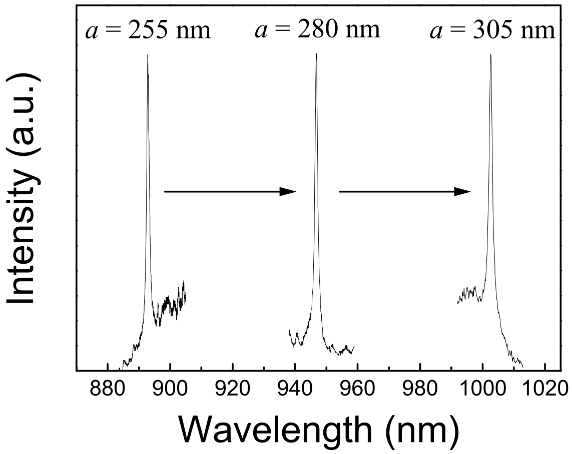

Figure 5. Measured photoluminescence spectra for H2 cavities with lattice constants **a.** 255 nm, **b.** 280 nm, and **c.** 305 nm. The cavity mode shifts from 893, to 948, to 1002 nm with increasing lattice constant.

fabrication process can lift the mode degeneracy. The modes in figure 4 correspond to pairs of symmetry degenerate eigenmodes which have been split by this perturbation. It is important to recognize this degeneracy has been lifted without any change to the microcavity design and yet the Q remains high. The separation of these ideally degenerate modes would allow strong coupling of the emission of a QD to a single cavity mode.

4.4. Spectral and Spatial Control of Emitters

If the emitter energy is out of spectral resonance with the cavity mode or the emitter is not at a field maximum, the observed coupling will be less than predicted by the Purcell factor. The final requirement for coupling is the ability to fabricate quantum dots with specific energies and control their position in the cavity. Currently, the accuracy to which the size/composition of QDs can be controlled (and hence the ground state energy) allows energies to be specified to better than 50 meV. Significant progress has been made in the area of spatial control. “Quantum dot lattices” have been made by patterning the substrate before nucleation to create a periodic strain field.[13] Nucleation takes place on top of patterned mesas to minimize the film energy forming a periodic arrangement of quantum dots. We believe these techniques allow sufficient spectral and spatial control for these coupling applications.

5. CONCLUSION

Photonic crystal microcavities offer the prospect of coupling a single mode of an optical cavity to a single semiconductor quantum dot. Measured cavity Q factors in these structures demonstrate they are already suitable for device applications in the weak confinement regime. The mode degeneracy is lifted by the imperfect nature of the fabrication process and yet the Q remains high. With the same techniques used to form “quantum dot lattices”, it should be possible to control the location of quantum dots within the cavity. The existence of nondegenerate high-Q cavity modes and the ability for spatial control of emitters also makes this system a good candidate for strong coupling.

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