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# Influence of Cavity Mode Emission on Single Photon Generation in Quantum-Dot-Cavity Systems

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## 1. Introduction

A single quantum dot (QD) in an optical cavity interacts with a radiation field through a single photon. As a result, the observed optical response of the QD is followed by photon generation according to non-Poissonian statistics, that is, single-photon generation with a number state. If the photonic environment is modified by a reduction in the effective mode volume ($V_m$) and an increase in the quality factor ($Q$), then one can realize single-photon emission with extremely high efficiency [1-4] and photon indistinguishability [5]. Recently, there have been several experiments reports on the off-resonant coupling between a single exciton and a single cavity mode in semiconductor microcavities [6-8]. A curious feature in these studies is much brighter cavity emission under large detuning ($\delta \neq 0$) than theoretically expected from standard emission formulas, and this has posed the question of whether the simple atom-like models of the QD fail. In this work, we undertake an experimental study to identify the cavity mode emission at non-zero detuning and investigate its influence on the photon statistics [9].

## 2. Results and Discussion

*Experimental Procedure*

A line-defect photonic-crystal (PhC) cavity with local width modulation [10] consists of a 200 nm-thick GaAs membrane containing a single InAs/InGaAs dot-in-well layer (Fig. 1). The cavity mode energy was tuned by using a thin gaseous film condensation technique [11], and the sample temperature was maintained at 4 K. To measure the second-order autocorrelation function of the emissions, a photon stream from the sample was fed into a fiber-based Hanbury Brown-Twiss interferometer after being passed through an in-line band-pass filter with a 1 nm linewidth.

*Origin of Cavity Mode Emission*

To have insights into the origin of the cavity mode emissions, we first performed PL measurements for individual QD cavities with various mode energies, as shown in Figs. 2(a) and (b). We used the excitation energy of 2.54 eV (Ar-ion laser, 10 μW) that is well above the GaAs barrier (1.52 eV at 4K), and 1.17 eV (YAG laser, 30 μW), which is slightly above the InGaAs quantum well (QW) bandgap (≈1.13 eV at 4 K). The observed cavity modes were indicated by shaded areas.

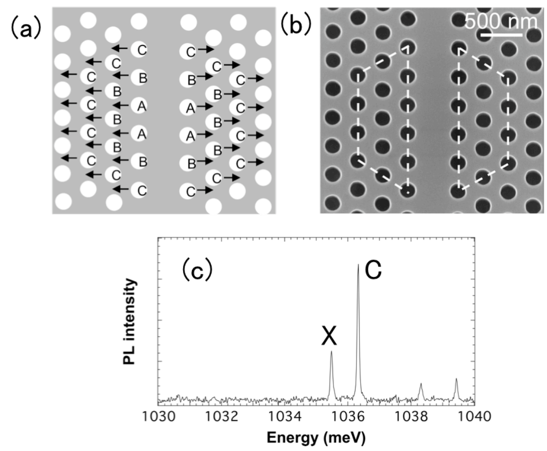


Fig. 1 (a) Schematic of the PhC system and (b) scanning electron microscope image. The air holes (A, B, C) were shifted 6, 4 and 2 nm outwards from their original positions, respectively. (c) Typical PL spectra of QDs in PhC cavity measured at 4K. Labels C and X indicate the emission form the cavity mode and single exciton, respectively.

Comparing Figs. 2(a) and (b), we found the general tendency that the cavity emissions are significantly brighter when excited high in the barrier, than excited just above the QW. Another finding is that when excited at 2.54 eV, irrespective of the cavity energies, the cavity mode emission intensity exhibits no apparent tendency to increase nor decrease, though the cavity emissions abruptly lose their intensity as the cavity energy decreases below about 1060 meV. Quite generally, one can assume deep lying radiative defect states as background emitters in each layer of the PhC slab. Since the deep state band tail in GaAs lies deep in the GaAs gap, likely forming a quasi-continuous spectrum, the cavity emission is observed in this measurement range with GaAs barrier excitation. Similarly, the deep state spectrum extends into the InGaAs QW gap, but the cut-off energy may be higher than in the GaAs case.

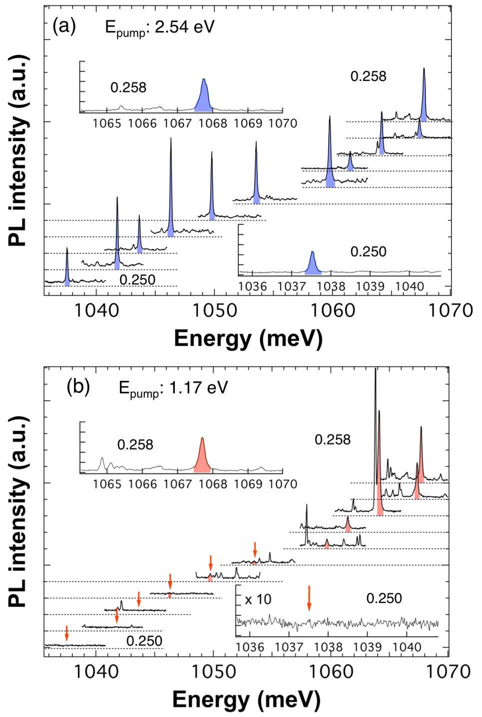


Fig. 2 (a) and (b) Series of PL spectra with various cavity mode energies which are varied by changing r/a ratio from 0.258 to 0.250. The excitation energies are (a) 2.54 eV and (b) 1.17 eV, and each spectrum between these is from completely the same cavity. Shaded areas correspond to the cavity mode emissions. The arrows in (b) indicate the cavity mode position, which is assumed by (a). Insets magnify the top and bottom spectra.

*Influence of Cavity Emission on Photon Statistics*

The left panel of Fig. 3 is image of PL intensity mapping with cavity mode detuning at 4 K. The GaAs barrier was also excited by Ar-ion laser (2.54 eV) in this measurement. The vertical axis in this image represents the number of thin-film condensation cycles. The integrated PL intensity when the cavity mode and the exciton are resonant (zero detuning), increases by a factor of about 9 compared with the off resonant case.

To explore the influence of the background emission on the photon statistics, we measured the second-order autocorrelation function of the photon intensity by the above barrier excitation. When off-resonant cavity mode ($\delta$ = 0.6 meV), anti-bunching was not observed where $g_C^{(2)}(0)$~1. This absence of the non-classical correlation on the cavity mode will be attributed to independently emitted photons from the background. The off-resonant exciton exhibited partial anti-bunching with $g_X^{(2)}(0)$=0.57, indicating that quantum mechanical coupling prevails. This may, however, be similar to uncoupled QD exciton case. Interestingly, at zero detuning the autocorrelation of the overlapping exciton and cavity modes shows a better anti-bunching with $g_{C+X}^{(2)}(0)$=0.35. As the exciton-cavity coupling is stronger, the relative weight of the deep states recombination con--tribution decrease, thereby the anti-bunching behavior is recovered to a better $g^{(2)}(0)$, indicating that the photon

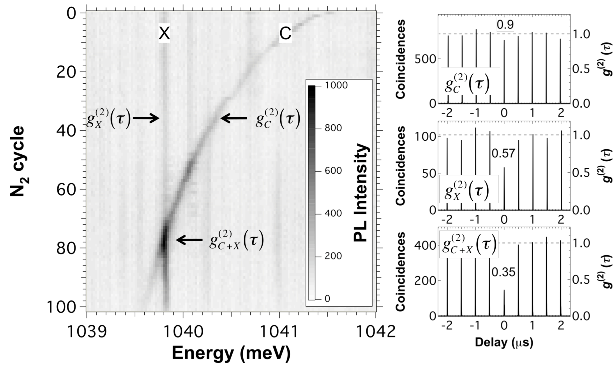


Fig. 3 (Left) PL intensity mapping with cavity mode detuning at 4 K. (Right) Measured second-order autocorrelation function of (a) $g^{(2)}{}_C(\tau)$, (c) $g^{(2)}{}_X(\tau)$, and (d) $g^{(2)}{}_{C+X}(\tau)$, respectively. The detuning of $g^{(2)}{}_C(\tau)$ and $g^{(2)}{}_X(\tau)$ are both $\delta$ = 0.6 meV. Each dashed line indicates $g^{(2)}(\tau)$ = 1.

statistics becomes more non-classical. These measurements will be qualitatively explained using a medium-dependent master equation model.

## 3. Conclusions

We have studied the origin of bright cavity mode emision with regarding the photon statistics in weakly copled QD - PhC cavity systems. We found that when excited above the GaAs barrier, the cavity mode emissions with nonzero detuning are most likely dominated by radiative recombination of the deep-level defects in the barrier layers. At zero detuning the autocorrelation of the overlapping exciton and cavity modes shows a better anti-bunching. As the exciton-cavity coupling is stronger, the relative weight of such background recombination contribution decrease, thereby the anti-bunching behavior is recovered to a better value, indicating that the photon statistics becomes more non-classical.


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