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A THEORETICAL STUDY OF MUTUAL COUPLING OF TWO SEMICONDUCTOR QUANTUM DOTS AND EVALUATION OF ITS PARAMETER

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Abstract: - Using the theoretical formalism of **A. Lauchet etal (Phys. Rev 82B, 075305 (2010))** and **Hyochul Kim etal (Optics Express, 19, 2589 (2011)),** we have theoretically studied a system consisting of two spatially separated self-assembled InGaAs quantum dots coupled to optical nano cavity mode. We observe that due to their different size and compositional profiles, the two quantum dots exhibit markedly different DC Stark effects. We have evaluated the spectral function of the system both as a function of applied bias voltages and also as a function of energy. Our theoretically evaluated results are in good agreement with the experimental data and also with other theoretical workers.

Keywords: Two semiconductor Quantum dots, Optical nano cavity, Cavity Quantum electrodynamics (CQED), Quantum optical non-linearties, Quantum confined Stark effects (QCSE), Photoluminescence (PL), Double dot-micropillar system, Double anti-crossing, Virtual photon emission, Excitonic transitions, Compositional profiles, Electron and Hole wavefunctions.

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INTRODUCTION

Quantum dots are semiconductor nanocrystals embedded in another semiconductor which presents a wide energy band gap between its valance and conduction states. This results in a three dimensional potential well that confine the carriers (electrons and holes) in the nano crystal. Here, the electron and hole motion is quantized in all the three spatial directions. This gives rise to discrete energy levels, each one accommodating up to two electrons and holes of opposite sign as in the case of single atoms. For this reason semiconductor quantum dots are often referred to as 'artificial atoms' that is a semiconductor analogue of a single atoms[1,2]. Quantum information science aims to explore the distinctive features of quantum physics especially superposition and entanglement, to enhance the functionality and power of information and communication technologies. It has been a progressing inter disciplinary field of research for last thirty years. It extends from the fundamental investigation of quantum phenomena to the experimental implementation of disruptive quantum-enabled technologies. In quantum information science, the information is encoded on a quantum bits consisting of any two level quantum system, its two states representing the degeits 0 and 1. Among quantum system, photons constitute a neutral choice for communications and metrology. This is a promising route for quantum simulation and computing. All these applications require ideally deterministic light source that can deliver on demand single photon, indistinguisble single photons or entangled photon pairs produced at high repetition rate. Several schemes have been established to produce such quantum states of light for example are attenuated lasers or non-linear optics. Presently, most experiments in quantum optics or photonic quantum information processing rely on non-linear optical sources. These sources allowing the preparation of time-beis[3] or polarization[4] entangled photons as well as heralded single photons[5]. Although down-conservation sources are still primarily employed due to high purity of the emitted quantum states of light, such sources suffer in particular from the probabilistic generation of photons combined with a trade-off between the repetition rate and the probability of emitting multiple photon pairs simultaneously.

Another scheme for generating efficiently and deterministically single photon states on demand uses the emission of a single quantum emitter, such as an atom[6,7], a ion[8,9,] a molecule[10,11] or a nitrogen-vacancy centre in dimand[12,13]. An attractive alternative for a solid state quantum system is that of semiconductor quantum dot. Cavity quantum electrodynamics experiments (cQED) using semiconductor quantum dots (QD) have attracted much interest in the solid-state quantum optics community[14,15] . Much progress has been made with a number of spectacular demonstrations including efficient generation of non-classical light[16], the observation and investigations of strong coupling phenomena[17-23] and the possibilities to observe and exploit quantum optical non-linear ties[24,25]. These developments are all ingredients for the realization of solid state all-optical quantum networks, when quantum memory elements are coupled via single light quanta. Imamoglu etal.[26] proposed that two spatially separated electron spins in QDs could be coherently coupled via a common optical cavity field. During last five years the strong coupling regime was reached for a single QDs and one observation was made with two dots coherently interacting with common cavity mode. This has provided a new way to entangle spatially separated quantum emitters via the electromagnetic quantum vacuum.

In this paper, we have theoretically evaluated the spectral function S(ω) of a system where two QDs are coherently coupled via an optical cavity mode. S(ω) were evaluated both as a function of applied bias voltage V_{app}(V) and as a function of QDs energy(mev). Our theoretically evaluated results are in good agreement with the other theoretical workers and also with the experimental data. We have also evaluated the temperature (K) for two mutually coupled QDs when they are resonance with the cavity mode as a function of wavelength (nm) for three values of magnetic field namely 5.5T, 5.75T and 5.9T. We observed that as the strength of magnetic field is reduced, each QD is coupled individually with cavity mode.

MATERIALS AND METHODS

One extends the model for single QD exciton[27] which includes two independently excitons coupled two independently excitons coupled to a common cavity mode

The Hamiltonian is written as

$$H=\sum_{n=1}^{2}[\frac{\hbar\omega_n}{2}\sigma^n{}_z+\hbar g_n(a^+\sigma^n{}_-+\sigma^n{}_+a)]+\hbar\omega_c a^+a \qquad (1)$$

Where $\sigma^n{}_+,\sigma^n{}_-$ and $\sigma^n{}_z$ are the pseudo spin operators for the two level system consisting of ground state $|0\rangle$ and a single exciton state $|X_n\rangle$ of the nth QD (n=1,2). ω_n is exciton frequency, a^+ and a are the creation and annihilation operators of photons in the cavity mode with frequency ω_c and g_n describes the strength of the dipole coupling between cavity mode and exciton of the nth-QD. The incoherent loss and gain (pumping) of the dot cavity system is included in the master equation of the Lindblad form

$$\frac{d\rho}{dt}=\frac{-i}{\hbar}[H,\rho]+\alpha(\rho) \qquad (2)$$

Where

$$\alpha(\rho)=\sum_{n=1}^{2}[\frac{\Gamma_n}{2}(2\sigma^n{}_-\rho\sigma^n{}_+-\sigma^n{}_+\sigma^n{}_-\rho-\rho\sigma^n{}_+\sigma^n{}_-)+$$
$$\frac{P_n}{2}(2\sigma^n{}_+\rho\sigma^n{}_--\sigma^n{}_-\sigma^n{}_+\rho-\rho\sigma^n{}_-\sigma^n{}_+)+\frac{\gamma^{\phi}{}_n}{2}(\sigma^n{}_z\rho\sigma^n{}_z-\rho)$$
$$+\frac{\Gamma_c}{2}(2a\rho a^+-a^+a\rho-\rho a^+a)+\frac{P_c}{2}(2a^+\rho a-aa^+\rho-\rho aa^+) \qquad (3)$$

Here Γ_n is the exciton decay rate, P_n is the rate at which excitons are created by a continuous wave pump laser, $\gamma^{\phi}{}_n$ is the pure dephasing rate of exciton in the nth-QD which accounts for effects originating from high exciton powers or high temperatures, Γ_c is cavity loss, P_c is the incoherent pumping of the cavity[28] and ρ is the density matrix of the system

Assuming that most of the light escapes the system through the radiation pattern of the cavity and using the Wiener-Khintchine theorem, the spectral function is given by[29]

$$S(\omega)\alpha\lim t\to\infty\,\mathrm{Re}\int_0^{\infty}d\tau\exp[-(\Gamma_r-i\omega)t]\langle a^+(t)a(t+\tau)\rangle \qquad (4)$$

Where $\hbar\Gamma_r$ is the half width added to take into account of the finite spectral resolution of double-monochromater[30]. The emission eigen frequency is obtained by solving the Liouvillian equation for the single time expectation value[31]

$$i\frac{\partial}{\partial t}\left(\begin{matrix}\langle a\rangle\\ \langle\sigma^1{}_-\rangle\\ \langle\sigma^2{}_-\rangle\end{matrix}\right)=\begin{pmatrix}\overline{\omega_c}&g_1&g_2\\ g_1&\overline{\omega_1}&0\\ g_2&0&\overline{\omega_2}\end{pmatrix}\left(\begin{matrix}\langle a\rangle\\ \langle\sigma^1{}_-\rangle\end{matrix}\right)$$

$$\langle \sigma^{2}{}_{-} \rangle) \quad (5)$$

Where

$$\overline{\omega_c} = \omega_c - i\gamma_c \quad 6(a)$$

$$\overline{\omega_n} = \omega_n - i\gamma_n \quad 6(b)$$

$$\gamma_c = \frac{(\Gamma_c - P_c)}{2} \quad 6(c)$$

$$\gamma_n = \gamma^{\phi}{}_n + \frac{(\Gamma_c + P_c)}{2} \quad 6(d)$$

The exciton-phonon coupling strength g is calculated using the formula

$$g = [\frac{\Delta E^2}{4\hbar^2} + \frac{(\gamma_c - \gamma_n)^2}{16}]^{\frac{1}{2}} \quad (7)$$

Where ΔE is the minimum energy separation between the two modes. γ_c and γ_n are the cavity and exciton rates respectively. From the eigen states of the emission eigen frequency, one obtains the degree of mixtures of each peaks in the spectrum i.e the strength of the contributions of cavity mode, QD1 exciton and QD2 exciton to each individual eigen states. In this calculation, one puts the following data

$$\hbar g_1 = 44\mu eV$$

$$\hbar g_2 = 51\mu eV$$

$$\hbar\Gamma_{QD1} = 0.1\mu eV$$

$$\hbar\Gamma_{QD2} = 0.8\mu eV$$

$$\hbar P_{QD1} = 1.5\mu eV$$

$$\hbar P_{QD2} = 1.9\mu eV$$

$$\hbar\gamma^{\phi}{}_{QD1} = 20\mu eV$$

$$\hbar\gamma^{\phi}{}_{QD2} = 9.8\mu eV$$

$$\hbar\Gamma_c = 147\mu eV$$

$$\hbar P_c = 5.7\mu eV \qquad (8)$$

Now in the case of study of optical properties of Quantum dot, the coupling strength between exciton-photon g is also calculated directly from the minimum energy splitting by similar type of formula as in equation (7)

$$g = [\frac{\Delta E^2}{4\hbar^2} + \frac{(\gamma_c - \gamma_s)^2}{16}]^{\frac{1}{2}} \qquad (9)$$

Where γ_c and γ_s are the cavity and exciton decay rate respectively. Now from the cavity Q, one can determine the cavity mode decay rate as

$$\gamma_c = \frac{\omega_c}{2\pi Q} = 36.4GH_z$$

$$\gamma_s = 0.16GH_z$$

One obtains the value of g_1 and g_2 as

$$g_1 = 13.8GH_z$$

$$g_2 = 14.8GH_z$$

Where g_1 and g_2 are the exciton-photon coupling strength of the state.

RESULTS AND DISCUSSION

Using the theoretical formalism of A. Laucht etal[32].and Houchul Kim etal[33]., we have theoretically studied the two spatially separated self-assembled InGaAs quantum dots strongly coupled to a single optical nanocavity mode. Due to their different size and compositional profiles, the two quantum dots exhibit markedly different DC Stark effects. This allows one to tune them into mutual resonances with each other and a photonic crystal nano cavity mode as a bias voltage is varied. **In table T1,** we have shown the results of Photoluminescence intensity (abs. Unit) of the exciton and biexciton emission as a function of the pulsed excitation power calculated by the use of single rate equation model[34]. Experimental results[35] are also shown with the theoretical results. **In table T2,** we have shown the results of the cavity mode, QD1 and QD2 for different bias voltage. This results emphasize the different DC starks effects of QD1 and QD2. Here, one observes two classes of lines to two different QDs with different size and In-Ga compositional profiles. This leads to two different distributions of the electron and Hole wave functions[36] and consequently different polarizabilities of the exciton transition. **In table T3**, we have shown the calculated and experimental results of spectral function. The calculation has been performed by taking the numerical data given in equation (8). Experimental results[37] were obtained from the best fit. Our theoretical results show that spectral function S(ω) has good quantitative agreement with the measuring data which supports the Lenenbeg-Marquardt equation[38]. **In table T4,** we have shown the calculated results of spectral function (PL intensity) (arb. Unit) in terms of QDs energy (mev). Our evaluated results are in good agreement with the observed values[39]. **In table T5,** we have shown the collective coupling behavior of two QDs when they are tuned into resonance with the cavity. The magnetic field is adjusted when they are resonance with each other. We have computed the temperature (K) as a function of wavelength (nm) for different magnetic field namely 5.5T, 5.75T and 5.9T. It has been found that wavelength separation between two QDs are 0.055nm at 5.9T, 0.035nm at 5.75T and negligible at 5.5T. As the magnetic field is tuned from 5.9T to 5.75T the detuning is decreased and the middle peak becomes weaker. When middle peak is fully suppressed then one obtains spectral doublet similar to the case when each QD is individually coupled to the cavity. There is some recent calculations[40-50] which also reveals similar type of behavior.

CONCLUSION

From the above theoretical analysis and investigations, we have come across the following conclusions

(1)We have studied theoretically a system where two QDs are coherently coupled via an optical cavity mode. Here, coupling has been established by electrically tuning both QDs into mutual resonance and into resonance with the cavity mode.

(2)Coupling can also be established by tuning in resonance with each other but detuning from the mode. This configuration offers the advantages that the photon loss from the cavity can be circumvented leaving the system in a state of coherent superposition for a longer time. It also relaxes the stringent criteria of extremely high mode Q-factors.

(3)One also observes that photoluminescence measurements show triple peaks which is a clear signature of coherently coupled system of three quantum states.

(4)The theoretical formalism of **A. Lauchet etal.** is able to investigate the coupling between the two quantum dots via the cavity mode. It also describes the coupling between when two dots are detuned from the cavity mode.

(5)The investigations of the collective coupling behavior of two QDs when they are tuned into resonance with the cavity the magnetic field is adjusted nearly on the resonance with each other. Our results show that as the magnetic field is reduced each QD is coupled to cavity.

Table T1

An evaluated results of photoluminescence intensity (PL)(arb. Unit) with the use of simple rate equation model[34] as a function of excitation power (nW) for exciton and biexciton emission for InGaAs quantum dot at 4K. Experimental results[35] were also shown with theoretical values

Excitation power P(nW)	**<----PL intensity (arb. Unit)----------------→**			
	Exciton(Theo)	Exciton (Expt)	Biexciton(Theo)	Biexciton(Expt)
10	58.6	60.5	----	------
50	87.3	92.8	----	------
100	112.6	120.4	16.5	20.8
150	127.2	130.9	38.4	42.3
200	138.4	142.6	65.3	71.6
500	147.9	153.4	78.6	82.9
700	263.8	271.5	112.7	117.9
900	873.5	880.2	156.6	163.5
1000	953.6	962.7	167.4	175.3
1500	1012.7	1016.4	462.8	487.4

TableT2

This table gives the PL spectra from the nano cavities rescaled using confocal microscopy as a function of applied bias voltage V_{app}(V). Energy(mev) of cavity mode, QD1 and QD2 are shown for different values of V_{app}(V)

Applied Bias Voltage V_{app}(V)	<-------Energy (mev)------------→		
	Cavity mode	QD1	QD2
-0.40	1217.8	1214.6	1216.9
-0.30	1218.2	1215.2	1217.3
-0.20	1219.7	1216.8	1218.6
-0.10	1220.6	1217.2	1219.0
0.00	1221.8	1218.6	1220.6
0.10	1222.3	1219.4	1221.8
0.20	1223.6	1220.8	1222.0
0.30	1224.5	1221.6	1223.2
0.40	1224.8	1222.5	1223.4
0.50	1225.0	1223.0	1224.6
0.60	1225.6	1223.6	1225.0

TableT3

An evaluated results of the spectral function S(ω) of two spatially separated self-assembled InGaAs quantum dots strongly coupled to a single optical nano cavity mode. The other parameters are taken from equation (8). Theoretical results were compared with the experimental data[37]

Applied Bias Voltage V_{app}(V)	<-----Energy (mev)------------→	
	S(ω)(Cal)	S(ω) (Expt)
0.20	1217.0	1216.2
0.25	1217.2	1216.6
0.30	1217.4	1217.2
0.35	1217.8	1218.0
0.40	1218.2	1218.6
0.45	1218.6	1219.2
0.50	1218.9	1219.8
0.55	1219.3	1220.0
0.60	1219.6	1220.5
0.65	1220.0	2121.0
0.70	1220.4	1221.7
0.75	1220.0	1222.0
0.80	1221.2	1222.5
0.85	1221.8	1222.9
0.90	1222.0	1223.0

TableT4

An evaluated results of spectral function (arb. Unit) are given as a function of QDs energy (mev) .Calculated results were compared with the measured values[39].

Energy (mev)	<------Spectral function (arb. Unit)-------→	
	Calculated	Experimental data
1217.0	2.674	2.705
1217.2	3.218	3.312
1217.4	4.129	4.156
1217.6	4.586	4.605
1217.7	4.862	4.884
1217.8	4.457	4.478
1218.0	3.586	3.609
1218.2	3.154	3.163
1218.4	2.876	2.857

Table T5

A theoretical study of collective coupling behavior of two QDs when they are tuned with resonance with cavity This table gives the theoretical evaluation of Temperature of the system as a function of wavelength(nm) for three different values of magnetic field namely 5.9T, 5.75T and 5.5T

Wavelength (nm)	Temperature (K)		
	5.5T	5.75T	5.9T
926.8	33.0	33.5	34.5
926.9	34.2	35.0	35.0
927.0	35.0	35.5	35.6
927.1	33.1	36.0	36.0
927.2	34.5	36.7	36.7
927.3	35.6	37.0	38.0
927.5	36.0	37.6	38.5

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