Research Article CODEN: IJPAKY Impact Factor: 4.226 ISSN: 2319-507X
Bhav Bhuti Narayan Mishra, IJPRET, 2015; Volume 4 (3): 79-92 IJPRET

INTERNATIONAL JOURNAL OF PURE AND APPLIED RESEARCH IN ENGINEERING AND TECHNOLOGY

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# A THEORETICAL EVALUATION OF EIGENVALUES AS A FUNCTION OF APPLIED BIAS VOLTAGE OF TWO QDS WHEN THEY ARE TUNED INTO EXACT RESONANCE WITH ONE ANOTHER

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Accepted Date: 05/10/2015; Published Date: 01/11/2015

**Abstract: -** Using the theoretical formalism of **A. Lauchet etal (Phys. Rev 82B, 075305 (2010),** 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 theoretically evaluated the eigenvalues of two QDs as a function of applied bias voltage when they are tuned into exact resonance with one another. We have presented the evaluated results of eigenvalues of (three branches of the double anticrossing of the two QDs) when they are detuned from the mode, $\lambda_0$ (upper panel) $\lambda_1$ (middle panel) $\lambda_2$ (bottom panel). The evaluation has been performed with the help of equation (5). These results indicate the exact evolution of three branches as a function of $V_{app}$. Our theoretical results indicate that eigenvalue is lowest in $\lambda_0$ panel and largest in $\lambda_2$ panel as a function of $V_{app}$. 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 , DC Stark effects, Exciton-photon coupling strength.

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**Access Online On:**

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**How to Cite This Article:**

Bhav Bhuti Narayan Mishra, IJPRET, 2015; Volume 4 (3): 79-92

***PAPER-QR CODE***

## INTRODUCTION

Quantum dots are extremely small semiconductor structures usually ranging from 2-10 nm (10-50 atoms) in diameter. At these small sizes materials behave differently giving quantum dots unprecedented tenability. These 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 an earlier paper[27], 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.

In this paper, we have evaluated the eigenvalues (probabilities) of three panels $\lambda_0$ (upper panel) $\lambda_1$ (middle panel) $\lambda_2$ (bottom panel) as a function of applied bias voltage $V_{app}$. We have also studied spectra in two cases (a) when obtained spectral signature could be due to two different single exciton transitions of the same quantum dot (b) by two different QDs one weakly and one strongly coupled to the cavity. Our obtained theoretical results are in good agreement with the other theoretical workers[28,29].

## MATERIALS AND METHODS

One extends the model for single QD exciton[30] 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). $\omega_n$ is exciton frequency, $a^+$ and a are the creation and annihilation operators of photons in the cavity mode with frequency $\omega_c$ 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 $\Gamma_n$ 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, $\Gamma_c$ is cavity loss, $P_c$ is the incoherent pumping of the cavity[31] and $\rho$ 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[32]

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

Where $\hbar\Gamma_r$ is the half width added to take into account of the finite spectral resolution of double-monochromater[33]. The emission eigen frequency is obtained by solving the Liouvillian equation for the single time expectation value[34]

$$i\frac{\partial}{\partial t}\begin{pmatrix}\langle a\rangle \\ \langle \sigma^{1}_{-}\rangle \\ \langle \sigma^{2}_{-}\rangle\end{pmatrix} = \begin{pmatrix}\overline{\omega_c} & g_1 & g_2 \\ g_1 & \overline{\omega_1} & 0 \\ g_2 & 0 & \overline{\omega_2}\end{pmatrix}\begin{pmatrix}\langle a\rangle \\ \langle \sigma^{1}_{-}\rangle \\ \langle \sigma^{2}_{-}\rangle\end{pmatrix} \qquad (5)$$

Where

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

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

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

$$\gamma_n = \gamma^{\phi}{}_{n} + \frac{(\Gamma_c + P_c)}{2} \qquad 6(d)$$

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

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

where ΔE is the minimum energy separation between the two modes. $\gamma_c$ and $\gamma_n$ are the cavity and exciton rates respectively. From the eigenstates 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

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

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

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

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

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

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

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

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

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

$$\hbar P_c = 5.7 \mu eV \tag{8}$$

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)

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

Where $\gamma_c$ and $\gamma_s$ are the cavity and exciton decay rate respectively. Now from the cavity Q, one can determine the cavity mode decay rate as

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

$$\gamma_s = 0.16 GH_z$$

One obtains the value of $g_1$ and $g_2$ as

$$g_1 = 13.8 GH_z$$

$$g_2 = 14.8 GH_z \tag{10}$$

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

In the eigenvalues calculations, one has contributions from cavity modes, QD1 and QD2 to three different branches of the system $\lambda_0$ (upper panel) $\lambda_1$ (middle panel) $\lambda_2$ (bottom panel). The coupling occurs via a Raman type of transition. We have also obtained spectra assuming that the states QD1 and QD2 cannot coexist. This is the case for two different state of the same QD i.e exciton and charged exciton . In this case the spectral function is the sum of the spectra of two independent quantum states

$$S(\omega)=S_1(\omega) + S_2(\omega) \qquad (11)$$

This gives double peak close to the resonance.

**RESULTS AND DISCUSSION**

In this paper using the theoretical formulism of **A. Laucht etal**[35], we have theoretically evaluated the eigenvalues of two QDs as a function of applied bias voltage when they are tuned into exact resonance with one another. In **table T1,** we have presented the evaluated results of eigenvalues of three branches of the double anticrossing of the two QDs when they are detuned from the mode, $\lambda_0$ (upper panel) $\lambda_1$ (middle panel) $\lambda_2$ (bottom panel). The evaluation has been performed with the help of equation (5). These results indicate the exact evolution of three branches as a function of $V_{app}$. Our theoretical results indicate that eigenvalue is lowest in $\lambda_0$ panel and largest in $\lambda_2$ panel as a function of $V_{app}$. In **table T2,** we have shown the theoretical results of probability (eigenvalue) of normalized admixture of QD1, QD2 and cavity mode to the quantum states of the coupled system for upper panel $\lambda_0$ as a function of $V_{app}$ (V). This is the individual states for different detuning as a function of $V_{app}$. Our theoretical results show that the probability decreases in case of QD1 and increases for QD2. However for cavity mode probability is very small. Here QD1 state and cavity mode state have only weak contribution of QD2 close to resonance. In **table T3,** we repeated the same calculation for $\lambda_1$ middle panel. Here we observed that in this case probability is large for QD2 for small values of $V_{app}$ but decreases up to 0.54V and then increases very fast. The probability of QD1 increases and have peak at 0.54V and then decreases. The probability of cavity mode is small in this case from 0 to 0.6V. The eigenvalue $\lambda_1$ is a mixture of all three states for $V_{app}$ =0.43V and it becomes only like QD1 for $V_{app}$=0.48V after that it behaves only like QD2 for $V_{app}$=0.6V. For large value of $V_{app}$ it remains like QD2 since the system is strongly detuned. In **table T4,** we repeated the calculation for $\lambda_2$ (bottom panel). Here cavity mode is large for small value of $V_{app}$ and then decreases up to 0.6V. QD2 increases and becomes mixture at 0.45V and then decreases slowly. In this case the probability of QD1 is small. $\lambda_2$ starts with cavity mode and becomes strongly mixed state of mode with QD2 and mixture of QD1 and QD2 for $V_{app}$=0.58V. In **table T5,** we have shown the evaluated results of spectral function as a function of $V_{app}$ assuming that QD1 and QD2 cannot coexist at the same time. This is the two different states of same QD i.e. exciton and charged exciton. Calculated results were compared with the experimental data[36]. In **table T6,** we have shown the evaluated results of spectral function (energy meV) as a function of $V_{app}$. Here we have assumed that QD2 is only weakly coupled to the cavity mode with fixed value of $\hbar g_2$ =32μV. Calculated results were compared with the experimental data[36] and perfect agreement has been found[37-43]. There is some recent calculations[44-55] which also reveals same type of behavior.

## CONCLUSION

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

(1)In case of QDs tuning there is resonance with cavity mode the system is in state of coherent superposition for longer time. It has external very high mode Q-factors.

(2)In the investigation of observed spectral function two possibilities arise (a) two different single exciton transition to the same quantum dot. (b) two different QDs, one is weakly and other is strongly coupled to the cavity mode.

(3) In the case of QD2 weakly coupled to the cavity mode, no exciton- polaritons are found. Spectral functions are not affected by the cavity mode

**Table T1 :An evaluated result of eigenvalue of the three branches of the double anticrossing of the two QDs when they are detuned from the mode, $\lambda_0$ (upper panel) $\lambda_1$ (middle panel) $\lambda_2$ (bottom panel)**

| Applied Voltage | <---- Eigenvalue (Energy, meV)------→ | | |
|---|---|---|---|
| $V_{app}$ (V) | $\lambda_0$ | $\lambda_1$ | $\lambda_2$ |
| **0.10** | 1217.27 | 1217.40 | 1217.58 |
| **0.20** | 1217.45 | 1217.55 | 1217.70 |
| **0.25** | 1217.56 | 1217.67 | 1217.75 |
| **0.30** | 1217.65 | 1217.75 | 1217.80 |
| **0.35** | 1217.72 | 1217.80 | 1217.85 |
| **0.40** | 1217.80 | 1217.90 | 1217.96 |

| | | | |
|---|---|---|---|
| **0.45** | 1217.85 | 1218.20 | 1218.37 |
| **0.50** | 1217.88 | 1218.32 | 1218.48 |
| **0.55** | 1217.90 | 1218.43 | 1218.62 |
| **0.60** | 1217.95 | 1218.54 | 1218.70 |

**Table T2: An evaluated result of probability (eigenvalue) of normalized admixture of QD1, QD2 and cavity mode to the quantum state of the coupled system for upper panel $\lambda_0$ as a function of applied bias voltage $V_{app}$(V). This is the individual states for different detuning as a function of $V_{app}$**

| **Applied bias voltage $V_{app}$** | **<---- $\lambda_0$(upper panel)(eigenvalue)----→** | | |
|---|---|---|---|
| | QD1 | QD2 | Cavity mode |
| **0.20** | 0.955 | 0.052 | 0.002 |
| **0.25** | 0.927 | 0.158 | 0.006 |
| **0.30** | 0.908 | 0.267 | 0.010 |
| **0.35** | 0.835 | 0.343 | 0.030 |
| **0.40** | 0.746 | 0.468 | 0.046 |
| **0.42** | 0.629 | 0.589 | 0.086 |
| **0.45** | 0.546 | 0.662 | 0.128 |
| **0.50** | 0.502 | 0.785 | 0.182 |
| **0.55** | 0.438 | 0.862 | 0.105 |
| **0.60** | 0.326 | 0.935 | 0.074 |

**Table T3: An evaluated result of probability (eigenvalue) of normalized admixture of QD1, QD2 and cavity mode to the quantum state of the coupled system for middle panel $\lambda_1$ as a function of applied bias voltage $V_{app}$(V). This is the individual states for different detuning as a function of $V_{app}$**

| **Applied bias voltage $V_{app}$** | **<---- $\lambda_1$(middle panel)(eigenvalue)----→** | | |
|---|---|---|---|
| | QD1 | QD2 | Cavity mode |
| **0.20** | 0.056 | 0.987 | 0.095 |
| **0.25** | 0.082 | 0.906 | 0.186 |
| **0.30** | 0.126 | 0.835 | 0.202 |
| **0.35** | 0.238 | 0.675 | 0.265 |
| **0.40** | 0.456 | 0.436 | 0.386 |
| **0.42** | 0.589 | 0.358 | 0.302 |
| **0.45** | 0.635 | 0.487 | 0.255 |
| **0.50** | 0.428 | 0.598 | 0.215 |

| | | | |
|---|---|---|---|
| **0.55** | 0.237 | 0.678 | 0.186 |
| **0.60** | 0.159 | 0.864 | 0.115 |

**Table T4: An evaluated result of probability (eigenvalue) of normalized admixture of QD1, QD2 and cavity mode to the quantum state of the coupled system for bottom panel $\lambda_2$ as a function of applied bias voltage $V_{app}$(V). This is the individual states for different detuning as a function of $V_{app}$**

| Applied bias voltage $V_{app}$ | <---- $\lambda_2$ (bottom panel)(eigenvalue)----→ | | |
|---|---|---|---|
| | QD1 | QD2 | Cavity mode |
| **0.20** | 0.056 | 0.126 | 0.958 |
| **0.25** | 0.082 | 0.208 | 0.903 |
| **0.30** | 0.125 | 0.305 | 0.875 |
| **0.35** | 0.186 | 0.396 | 0.786 |
| **0.40** | 0.209 | 0.458 | 0.654 |
| **0.42** | 0.246 | 0.532 | 0.585 |
| **0.45** | 0.489 | 0.436 | 0.495 |
| **0.50** | 0.686 | 0.297 | 0.335 |
| **0.55** | 0.855 | 0.185 | 0.274 |
| **0.60** | 0.952 | 0.102 | 0.186 |

**Table T5: An evaluated result of Spectral function (energy, meV) as a function of applied bias voltage $V_{app}$ (v) assuming that QD1 and QD2 cannot coexist at the same time We have compared our theoretical results of spectral function with the experimental data[36].**

| Applied Bias voltage $V_{app}$(V) | <--Spectral function (energy, meV)--→ | |
|---|---|---|
| | Calculated | Experimental |
| **0.20** | 1217.11 | 1217.05 |
| **0.25** | 1217.18 | 1217.08 |
| **0.30** | 1217.32 | 1217.19 |
| **0.35** | 1217.39 | 1217.25 |
| **0.40** | 1217.52 | 1217.34 |
| **0.45** | 1217.60 | 1217.46 |
| **0.50** | 1217.22 | 1217.54 |
| **0.55** | 1217.35 | 1217.16 |
| **0.60** | 1217.58 | 1217.28 |
| **0.65** | 1217.40 | 1217.47 |
| **0.70** | 1217.34 | 1217.36 |

**Table T6: An evaluated result of spectral function (energy, meV) as a function of applied bias voltage $V_{app}$ (V) assuming that QD2 is only weakly coupled to the cavity mode with fixed $\hbar g_2$ =32µV. We have compared our theoretical results of spectral function with the experimental data[36].**

| Applied Bias voltage $V_{app}$(V) | <--Spectral function (energy, meV)--> | |
|---|---|---|
| | Calculated | Experimental |
| 0.20 | 1217.22 | 1217.17 |
| 0.25 | 1217.31 | 1217.25 |
| 0.30 | 1217.36 | 1217.29 |
| 0.35 | 1217.42 | 1217.38 |
| 0.40 | 1217.56 | 1217.53 |
| 0.45 | 1217.68 | 1217.62 |
| 0.50 | 1217.47 | 1217.43 |
| 0.55 | 1217.35 | 1217.30 |
| 0.60 | 1217.58 | 1217.54 |
| 0.65 | 1217.46 | 1217.41 |
| 0.70 | 1217.33 | 1217.30 |

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