Weak Coupling Regime of MOCVD Dots Coupled to Photonic Crystal Nanocavity

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Abstract— **We show the deterministic coupling of the MOCVD InGaAS/GaAs dots to photonic crystal nanocavities.**
The unique properties of the fabrication technique offer a complete control on the emission properties due to the small inhomogeneous broadening of QDs inside the photonic crystal.
The PL-Spectroscopy of the system shows that the coupling of the QDs to photonic crystal nanocavity is satisfied with a small mismatch of 50 nm in wavelength.
We discuss the weak coupling regime theoretically and show that how spontaneous emission can be enhanced by putting the dots inside photonic crystal nanocavity.
We have checked the enhancement of spontaneous emission as a direct result of Purcell effect.
The system can be used as an efficient source of solid state single photon emission for quantum computing, quantum cryptography as well as for fundamental quantum optics experiments such as cavity QED experiments.

Index Terms—**Photonic Crystal, Quantum Dots, Spontaneous Emission, Weak Coupling Regime**

I. INTRODUCTION

In recent years the coupling of single emitters to different types of nanocavitieshas has widely been studied.
The most important early works focused on the trapping of atoms in single mode operating small cavities.
But the systems suffered from different types of problems one of which is the difficulty in the trapping single atom [1].
Also the long time needed for keeping the structure stable, is another problem of the trapped atoms in cavities to study light-matter interaction.
This problem have been solved by laser cooling method, but still the structure suffers from difficult technical problems related to optical, magnetic or magneto-optical traps' structures.
So, QDs inside PC Nanocavities are promising source for studying coupling regimes and cavity QED experiments in stable times, because QDs are fixed inside the cavity during growth procedure.
,.MBE dots inside different kinds of cavities, such as micro disks, micropillar, photonic crystal slab, and highly reflected mirror resonators have been studied and well understood, however there is still a room for considerable effort that can be done in the subject, our system of coupled MOCVD InGaAs/GaAs coupled to Photonic Crystal nanocavity provides a unique method to study coupling regimes due to the high control and freedom of design that we have during growth procedure.
In section II, we will discuss the theoretical motivations to study the cavity structure in order to carry out CQED experiments.
Section III, is dedicated to experimental resultss during which FDTD simulation results are shown and the coincidence between simulation and experiment is evidenced.
PL-Spectroscopy measurements of the system in different temperatures are shown and we see that QDs are coupled to Photonic Crystals with 50 nm mismatch.
Our measurements show a quality factor of 3000, which is in good agreement with FDTD simulations which predict a cavity with a quality factor of 3200.
In section IV, we briefly discuss the weak coupling regime (WKR) theoretically and investigate the Purcell factor and using time-resolves spectroscopy we see that the emission rate of our dots is increased inside cavity.
Finally the paper ends with summary, conclusion and future outlooks.

II. THEORETICAL MOTIVATION

In order to investigate the cavity QED experiments, one should have a simple definition of cavity QED; e.g. it is the interaction between a quantum emitter and a single mode optical field.
Here the quantum emitter is considered to be the two level atomic like dot and the single mode optical field is captured inside our photonic crystal.
In order to perform our experimental measurements, dot(s) should be in resonance with photonic crystal cavity mode both spectrally ($\lambda = \lambda_{cav}$) and spatially (dot(s) should be located at the field maximum, where $E = E_{Cav}$), Also the dipole moment should be aligned with the electric field ($\mu \| E$) [1].
In order to fabricate the appropriate structure, we need a cavity with high quality factor (Q factor),
Because when a radiation source is placed inside the cavity, its radiation energy will be distributed among all modes; the system will, after a short time, again reach thermal equilibrium at a correspondingly higher temperature.
Because of the large number of modes in such a closed cavity, the mean number of photons per mode (which gives

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the ratio of induced to spontaneous emission rate into the mode) is very small in the optical region.

So, closed cavities with $L >> \lambda$ (L=the length of cavity and λ = the optical wavelength) are therefore not suitable as laser resonators or quantum optical devices.

In order to achieve a concentration of the radiation energy into a small number of modes, the resonator should exhibit a strong feedback for these modes, but large losses for all other modes, this would allow an intense radiation field to be built up in the modes with low losses but would prevent the system from reaching the oscillation threshold in the modes with high losses.

Assume that the kth resonator mode with the loss factor β_k contains the radiation energy W_k, the energy loss per second in this mode is then:

$$\frac{dW_k}{dt} = -\beta_k W_k \qquad (1)$$

We define the quality factor Q_k of the kth cavity mode as 2π times the ratio of energy stored in the mode to the energy loss per oscillation period T=$\frac{1}{\upsilon}$

$$Q_k = -\frac{2\pi\upsilon W_k}{dW_k/dt} \qquad (2)$$

We can relate the loss factor β_k and the quality factor Q_k by:

$$Q_k = \frac{-2\pi\upsilon}{\beta_k} \qquad (3)$$

After the time $1/\beta_k = \tau$, the energy stored in the mode has enhanced to $1/e$ of its value at t=0.

This time can be regarded as the mean lifetime of a photon in this mode.

If the cavity has large loss factors for most modes, but a small β_k for a selected mode, the number of photons in this mode will be larger than in the other modes, even if t=0, the radiation energy in all modes was the same.

Also we need a cavity with a small volume, because a good cavity or resonator is defined with the ratio of Q/V, this ratio becomes different for various applications, but the main purpose is to maximize this fraction [2].

V is the cavity mode volume:

$$V = \left|\int \varepsilon(\vec{r})\left|\vec{E}(\vec{r})\right| d^3(\vec{r})\right|^2 / \max\left\{\varepsilon(\vec{r})\left|\vec{E}(\vec{r})\right|^2\right\} \qquad (4)$$

MOCVD growth method gives us freedom to play with dot's size and shape, because according to the Schrodinger equation for a spherical dot we have:

$$E_{n,l} = \frac{\hbar^2 \chi^2_{n,l}}{2m^* a^2} \qquad (5)$$

As it is seen from the Eq.(5), exiton wavelength in a dot is dependent on dot's size and shape, so by controlling the shape and size of a dot during MOCVD process, one can play with exiton wavelength[3].

III. Experimental results

The MOCVD growth of quantum InGaAs dots as small as 150-300 nm is performed on $(111)_B$ GaAs substrate.

Bigger dots around them, act as sacrifice dots.

The photonic crystal is fabricated using EBL technology with a definite $\frac{r}{a}$ (r=radius of the dots and a =pitch between dots) ratio and h (=depth of the holes).

The cavity structure is designed using FDTD method with maximum dot and optical field mode interaction, i.e. $\langle \vec{\mu}.\vec{E} \rangle$ is maximized.

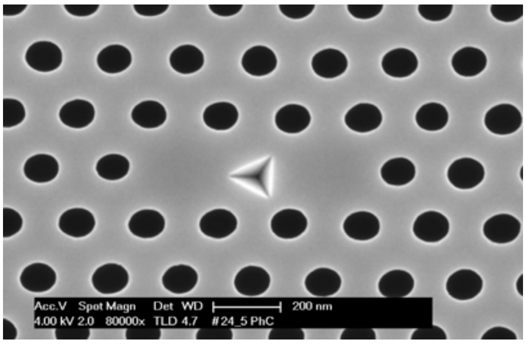

Fig.1. SEM picture of Dots inside Photonic Crystal Nanocavity

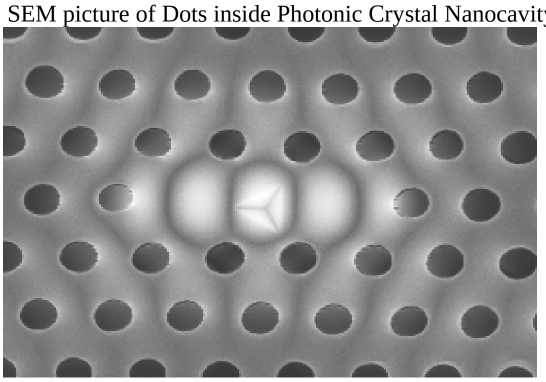

Fig.2. 2-Dimentional FDTD simulations of Photonic Crystal nanocavity with inserted dots mixed with SEM picture

After growth and processing of the system, we perform the PL-Spectra measurements performed both on ensembles of InGaAs/GaAs dots and single dot to characterize the spectrum of the system.

Also PL-Spectroscopy measurements are performed in different temperatures.

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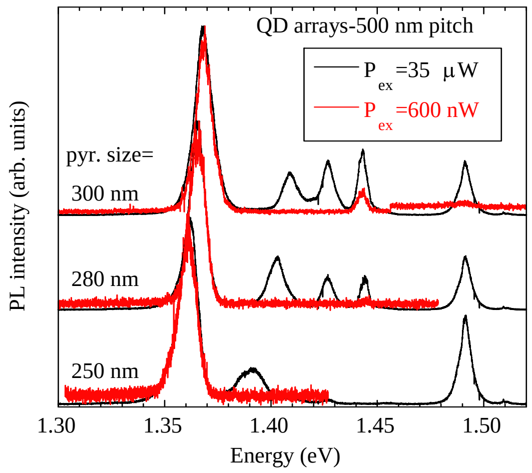

Fig.3.PL-Spectra of ensembles of InGaAs/GaAs dots

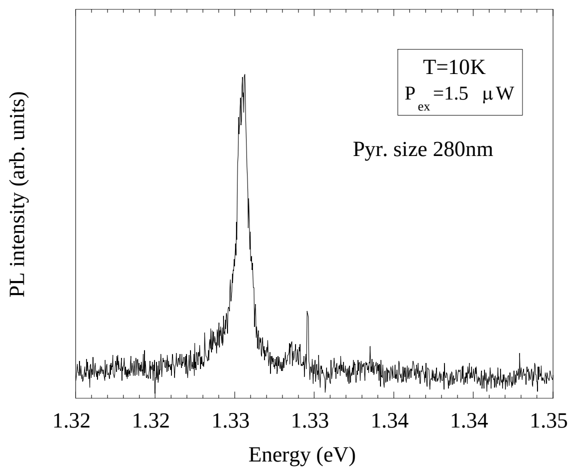

Fig.4.PL-Spectra of an InGaAs/GaAs dot

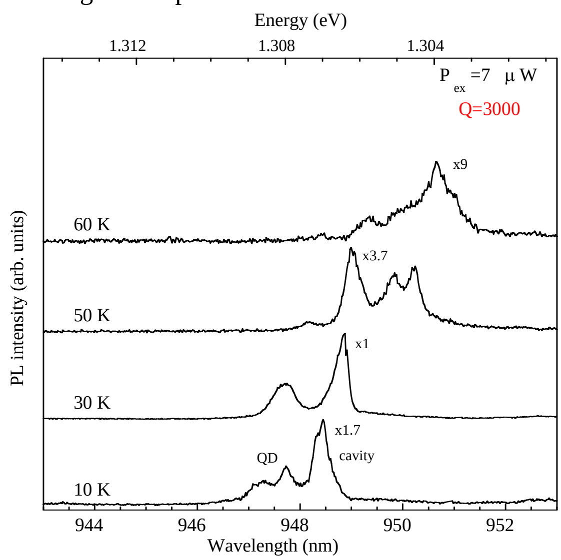

Fig.5.Single QD PL-Spectra in a Photnic Crystal Cavity

As shown in Fig.3. the PL-Spectrum of a QD inside a photonic crystal nanocavity has a blue-shift with increasing temperature, but the cavity mode peak has a very small shift due to the dependence of the refractive index of cavity with temperature.PL-spectrum shows that our dots work in 930-950 nm wavelength, and cavity Q factor is 3000 which is in good agreement with our simulation predictions of 3200.

IV. Weak Coupling Regime

The quality $\frac{Q}{V}$ shows the ability of a cavity to confine photons wave packets. For example in weak coupling regime, we are interested in maximizing $\frac{Q}{V}$, but for nonlinear optical effects $\frac{Q^2}{V}$ is to be maximized, and or for the strong coupling regime $\frac{Q}{\sqrt{V}}$ is to be investigated [1].

Other than the ratio of $\frac{Q}{V}$ to qualify a cavity itself, we have to investigate that how good an emitter is coupled to a nanocavity, we consider our dots as a two level atomic like system which is coupled to a cavity, and the following figure shows the system schematically:

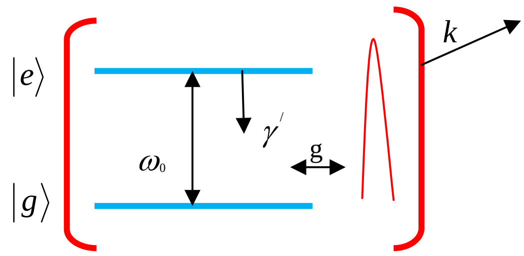

Fig.6.Schematic diagram of a QD inside a Cavity

As illustrated in the figure, three parameters are important, γ', g and k, which are irreversible decay rate of dot inside cavity , coupling strength between a dot and cavity and irreversible decay rate of cavity respectively.

In satisfying the so-called weak coupling regime (WKR) the irreversible decay rates k and γ' should dominate over the Hamiltonian dipole interaction between the dot and the cavity mode, whose strength is given by g, i.e.:

$$\gamma',\ k >> g \tag{6}$$

Now the question is that, how to satisfy the relation (6)?

If we consider the localized dipole (dot) with a wavelength of λ_e, and linewidth $\Delta\lambda_e$, placed on resonance with a single cavity mode with wavelength λ_c and linewidth $\Delta\lambda_c$, and quality factor $Q = \frac{\lambda_c}{\Delta\lambda_c}$, since $\Delta\lambda_e << \Delta\lambda_c$,

the escape time of SE photons out of the cavity is much shorter than the radiative lifetime and reabsorption is negligible, that is SE is not an irrevirsible process, because Schrödinger equation always leads to reversible dynamics.

But in order to satisfy the WKR condition, the modes of the electromagnetic field are treated as a Markovian reservoir; that is, a reservoir with infinitely short memory that irreversibility is achieved, in other words the cavity photon lifetime is much shorter than the emitter's, so that the cavity photon just interacts with emitter and let it leave, and the dephasing rates of γ' and κ over come g.

So the conditions γ', $\kappa >> g$ and $\Delta\lambda_e << \Delta\lambda_c$ are equivalent to the Markovian or short memory reservoir and the Hamiltonian can be solved perturbation theory.

In Wigner-Weisskopf approximation, the emission rate is proportional to LDOS [4].

The total spontaneous emission rate of a QD, γ, with detuning of amount $\lambda - \lambda_{cav}$, is:

$$\gamma' = \gamma_{cav} + \gamma_{PC} \tag{7}$$

Quantum Mechanical treatment of a two level system such as dot interacting with a quanta of an electromagnetic field describes that the spontaneous emission is no longer the intrinsic character of such system, but rather results from the coupling of the quantum emitter dipole moment to the vacuum modes of the electromagnetic field, so, it can be modified by tailoring the electromagnetic environment that the atom can radiate into, this was already realized by Purcell. The spontaneous emission rate of a dot inside the cavity which is derived from Fermi Golden Rule in Jaynes-Cummings model using perturbation theory:

$$\frac{\gamma'}{\gamma_0} = \frac{3\lambda_c^3}{4\pi^2 n^3}\frac{Q}{V}\left|\frac{\vec{E}.\vec{\mu}}{E_{max}\,\mu}\right|^2 \frac{\Delta\lambda_c^2}{\Delta\lambda_c^2 + 4(\lambda-\lambda_c)^2} \tag{8}$$

Which the Purcell factor is:

$$\frac{3\lambda_c^3}{4\pi^2 n^3}\frac{Q}{V} \tag{9}$$

So, for sufficiently high quality factors and transition wavelengths comparable to the linear dimensions of the cavity, this expression predicts a considerable enhancement of the spontaneous emission rate as compared to its free space value if and only if the emitter is in a good resonance with its cavity ($\lambda_c \approx \lambda$).
Also, this factor describes the ability of a cavity in coupling an ideal emitter with the vacuum field, via local enhancement of its intensity (small V's) or of the effective mode density (high Q's).
By measuring the time-resolved spectroscopy of QDs inside photonic crystal cavity we observe the increasing of the spontaneous emission rate of the dots resonantly coupled to photonic crystal cavity.
All other spontaneous emissions are suppressed because of mode selection in our cavity.
The following figure indicates time-resolved spectroscopy of the system,

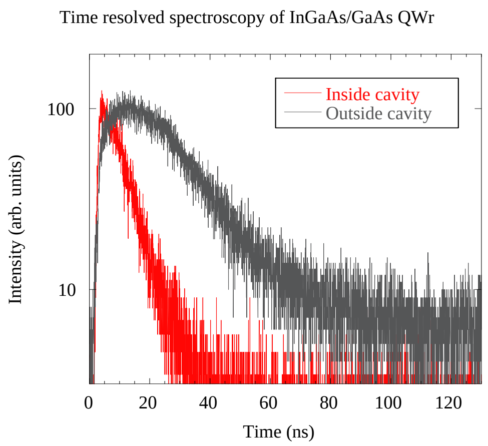

Fig.7.Time-resolved spectroscopy of QDs inside Photonic Crystal Nanocavity

V. SUMMARY AND CONCLUSION

We discussed the coupling method of QDs into Photonic Crystal nanocavity, and how to maximize $\frac{Q}{V}$ ratio in order to reach the optimum coupling of dots and PC nanocavity,then we measured PL-intensity of the system to investigate that how resonantly QD and Photonic Crystal are coupled with each other.
Our experimental results show that the dots work in 930-950 nm wavelength and they are coupled with PC nanocavity with 50 nm mismatch.
Also the quality factor of cavity is 3000 according to our measurements which has a good coincidence according to our predictions of 3200.
Also we discussed how to reach the weak coupling regime in our system and how to enhance the spontaneous emission rate of dots inside PC nanocavity.
We observed the enhancement of the spontaneous emission rate due to the Purcell factor.
The system has a high potential to be used as an efficient single photon source and to investigate strong coupling regime.
By fabricating the coupled dots inside the cavity, it is also possible to explore the photon mediated exiton entanglement in such a complex system.

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