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Cavity-quantum electrodynamics using a single InAs quantum dot in a microdisk structure

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We investigate cavity-quantum electrodynamics (QED) effects in an all-semiconductor nanostructure by tuning a single self-assembled InAs quantum dot (QD) into resonance with a high quality factor microdisk whispering gallery mode (WGM). The stronger temperature dependence of the QD single-exciton (1X) resonance allows us to change the relative energy of the WGM and the 1X transitions by varying the sample temperature. The two coupled resonances exhibit *crossing behavior* due to the weak coupling cavity-QED regime. We demonstrate exciton lifetime reduction by 6 due to the Purcell effect by tuning the QD into resonance with the WGM. Our experiments also show that single-exciton lifetime is independent of temperature up to 50 K. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1379987]

Recent observation of ultrasmall linewidths[1–3] and photon antibunching[4,5] in the fluorescence of single semiconductor quantum dots (QDs) have unequivocally demonstrated their atom-like nature. These results suggest that single QDs can be utilized to investigate fundamental quantum optical systems in semiconductor nanostructures. Cavity-quantum electrodynamics (cavity-QED) stands out among these fundamental systems due to the simplicity of its theoretical description and the wide range of its applications. Depending on the coupling strength between the two-level emitter and the cavity mode, spontaneous emission can be enhanced (weak coupling regime) or becomes *reversible* (strong coupling regime).[6] Purcell effect and vacuum Rabi oscillations are the best known experimental signatures of the weak and strong coupling regimes, respectively. Realization of these cavity-QED effects could enable applications such as high speed light sources and quantum information processing.[7]

In this letter, we report the experimental observation of the Purcell effect from a single self-assembled InAs QD coupled to a high quality factor (Q) microdisk whispering gallery mode (WGM) together with an important tool for investigating coupling between a single QD and a three-dimensional optical microcavity mode, i.e., temperature tuning. Our experiments demonstrate the crossing between a QD single-exciton (1X) transition and a WGM as a function of temperature. From photon correlation measurements performed in and out of resonance, we deduce that at resonance the lifetime of the 1X transition is shortened by a factor of 6 due to the Purcell effect. We also report the results of time correlated single photon counting experiments performed on another QD that show similar 1X-transition lifetimes at 4 and 50 K when the transition is out of resonance with WGMs. We note that enhancement of spontaneous emission from an ensemble of QDs due to the Purcell effect has been recently demonstrated.[8,9] In contrast, this letter reports an observation of the Purcell effect from a single QD.

The QD sample was grown by molecular beam epitaxy on a semi-insulating GaAs substrate. Layers of the sample were 0.5 μm $Al_{0.65}Ga_{0.35}As$ post layer and 200 nm GaAs disk layer. Self-assembled InAs QDs were grown in the center of the 200 nm disk region using the partially covered island technique.[10] The wavelengths of the 1X transitions of the QDs were between 925 and 975 nm. The QDs had a diameter of 40–50 nm and a height of 3 nm. The QD density of the sample was $\sim 2\times10^6\ \mathrm{cm}^{-2}$. Microdisks were processed using a two-step wet-etching procedure detailed elsewhere.[11] The diameters of the microdisks were 5 μm.

The sample was mounted in a He-flow cryostat allowing for temperature tuning from 4 to 300 K. A cw TiSa laser emitting at 760 nm was used to pump the microdisks, generating carriers in the GaAs disk layer. Excitation and collection were done through the same objective (numerical aperture$=$0.55) in normal direction (diffraction limited spot size: 1.7 μm). The collected photoluminescence (PL) was dispersed by a 50 cm spectrometer (spectral resolution: 70 μeV) and detected by a charge coupled device detector for measurements of optical spectra or by a Hanbury Brown and Twiss (HBT) setup[12] (time resolution: 420 ps) for photon correlation measurements. Reference 5 provides the details on the HBT setup. Despite the fact that the microdisk WGM radiation was primarily in the plane of the disk, we were able to detect the WGMs in normal direction using our setup, due to the high numerical aperture of the collection microscope objective, scattering caused by the disk surface and reflection from the sample surface.

Figure 1 shows high-resolution PL spectra of a single

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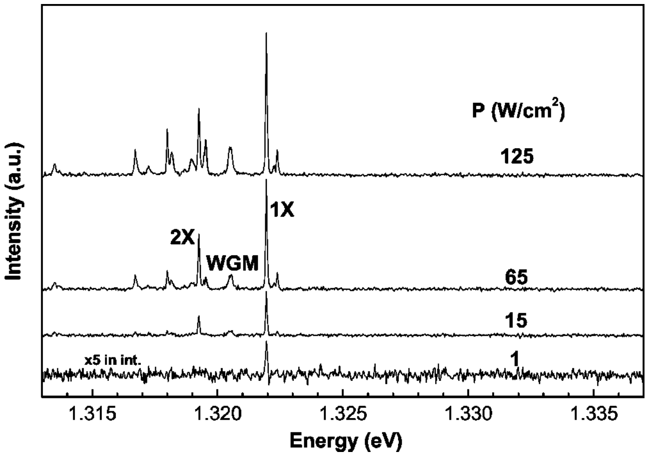

FIG. 1. Power dependent PL spectra of a single QD in microdisk cavity taken at 4 K. Luminescence of the QD 1X transition, the WGM, higher exciton lines, and contributions of other WGMs are visible.

QD with a WGM taken at 4 K for different excitation powers. In the lowest excitation power, only one peak with resolution limited linewidth (70 μeV) appears at an energy of 1.3219 eV. We identify that peak as the QD 1X transition. This identification is further supported by the results of the photon correlation measurements shown in Fig. 2 that will be discussed later. From the power dependent PL spectra shown in Fig. 1 we identify the WGM by its relatively large linewidth of 200 μeV. The linewidth of the WGM corresponds to a Q value of 6500. We note that the source of the WGM radiation at 4 K is not clearly identified, it might be caused by the residual emission from the GaAs disk. Temperature dependent characteristics plotted in Fig. 2 provide additional evidence for the identification of the WGM.

Figure 2 shows several aspects of the coupling between the WGM and the 1X transition depicted in Fig. 1 observed as a result of temperature tuning. The crossing between the two resonances is demonstrated in Fig. 2(a) where we plot the energies of the two lines versus temperature. The WGM appears at an energy of 1.3207 eV at 4 K and shifts only slightly to an energy of 1.3196 eV at 54 K while the 1X transition shifts by over 3 meV within 50 K temperature difference. The different energy shifts of the 1X transition and the WGM with temperature give rise to a crossing of the two resonances. The temperature dependence of the energy of the WGM can be attributed to the change in the refractive index of GaAs with temperature. On the other hand, the temperature dependence of the energy of the 1X transition is caused by the changes in the band gaps of InAs and GaAs with temperature. Figure 2(b) shows the change in the intensity of the WGM emission as a function of the 1X–WGM detuning under the same excitation conditions. At a temperature of 44 K (zero detuning) the intensity of the WGM luminescence increases by a factor of 29 compared to its value at 4 K, strongly indicating a resonance between the 1X transition and the WGM. In resonance, residual emission in the WGM is thus negligible (3%) compared to the emission due to the 1X transition.

In the weak coupling regime, enhancement of the spontaneous emission rate of the QD 1X transition due to the Purcell effect[13] is expected. For our specific WGM, an ideal Purcell effect of $F_P = 17$[14] can be estimated, while spatial mismatch between the QD and WGM would result in a smaller value. In our case, the precise location of the QD within the disk is not known, preventing us from determining the expected Purcell effect. To quantify the magnitude of the Purcell effect we have carried out pump-power dependent cw photon correlation measurements; this method has been previously shown to be a reliable alternative to standard time-resolved measurements for determining recombination

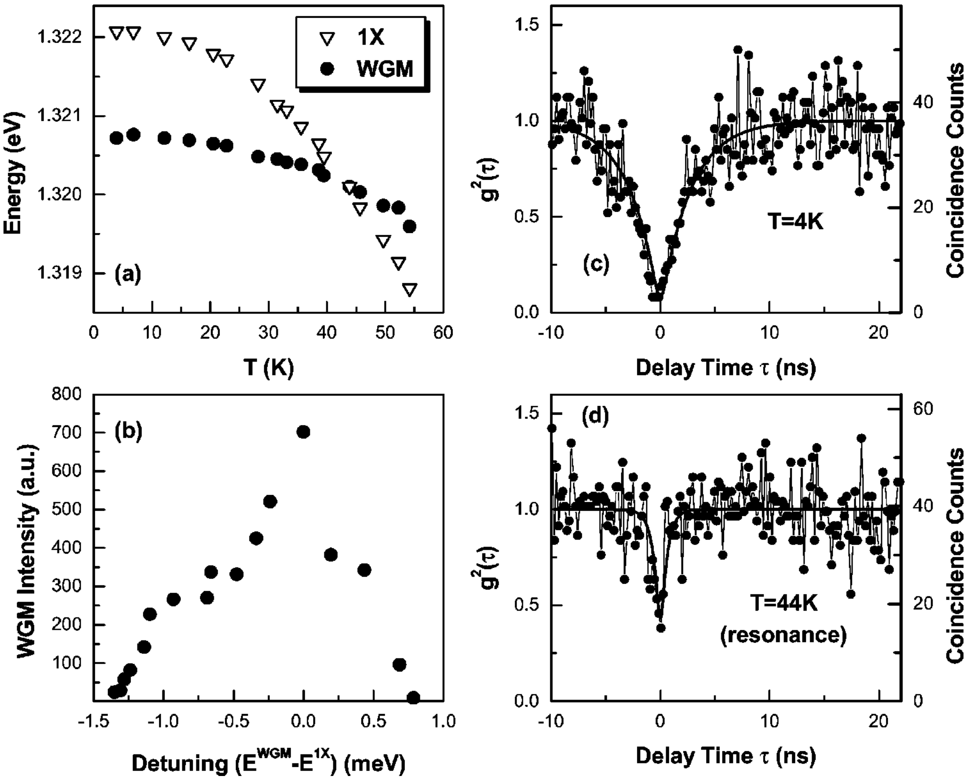

FIG. 2. (a) Change of the WGM and the 1X-transition emission energy with temperature (excitation power $=15$ W/cm^2). (b) Change in the intensity of the WGM luminescence with 1X–WGM detuning (excitation power $=15$ W/cm^2). Measured photon correlation function of the 1X transition of the single QD: out of resonance with the WGM, at 4 K, under an excitation power of 35 W/cm^2 (c), and in resonance with the WGM, at 44 K, under an excitation power of 5 W/cm^2 (d).

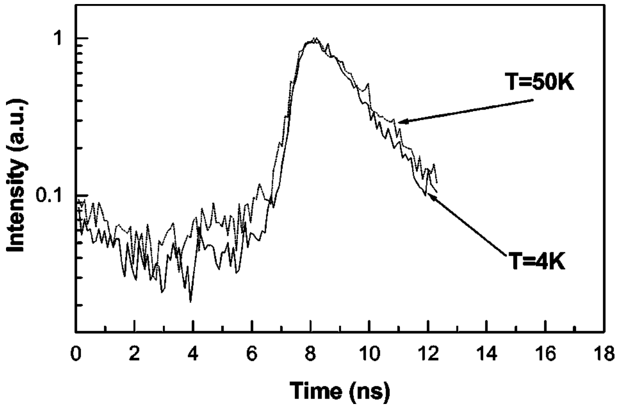

FIG. 3. Time correlated single photon counting measurements on the 1X transition of a QD at 4 and 50 K, out of resonance with any WGMs.

times.[5] Figures 2(c) and 2(d) show photon correlation measurements performed at 4 K (out of resonance) and 44 K (in resonance) with excitation levels below saturation of the 1X transition (35 W/cm^2 at 4 K and 5 W/cm^2 at 44 K).[15] After normalization, the measured correlation functions show clear dips at zero time delay [$g^{(2)}(0)=0.08$ at 4 K, $g^{(2)}(0)=0.38$ at 44 K] indicating strong photon antibunching. Since $g^{(2)}(0)<0.5$ in our measurements, we can state that the observed emission lines are primarily due to the 1X transition of a single QD.[5] Hence, in resonance, the 1X transition is the main emission feeding the WGM luminescence. We explain the value of $g^{(2)}(0)$ in Fig. 2(b) being 0.38 instead of the ideal value of 0 by the short decay time (560 ps) which is comparable to the time resolution of the HBT setup (420 ps).

From photon correlation measurements at two different pump powers, we deduced the lifetime of the 1X transition at 4 K. In these measurements, decay times of 2.7 and 1.5 ns were observed at excitation levels below saturation [35 W/cm^2, Fig. 3(a)] and at the onset of saturation (90 W/cm^2) of the 1X transition, respectively. From a three-level rate-equation model that includes 1X and biexcitonic transitions and omits any higher multiexcitonic recombinations or any other population decay channels (e.g., Auger processes),[5] a lifetime of 3.4 ns is determined for the 1X transition at 4 K. This value is larger than previously reported lifetimes for the 1X transition of single InAs QDs ($\sim$1 ns). This lifetime difference can be explained by the different photonic environment created by the microdisk that partially inhibits spontaneous emission.[5] This phenomenon should also be taken into account in the quantitative estimation of the Purcell effect in such structures.

Our photon correlation measurements at resonance, 44 K, revealed decay times of 560 ps and 370 ps at pump powers of 5 W/cm^2 [Fig. 3(b)], and 45 W/cm^2, respectively, corresponding to excitation levels below the saturation of the 1X transition. By using the pump power dependent method described in the previous paragraph, a lifetime of 590 ps is determined for the 1X transition at 44 K. Comparing the lifetimes in and out of resonance, and by assuming the effects of the nonradiative recombination to be negligible in both measurements, we deduce an enhancement in the spontaneous emission rate of the 1X transition by a factor of 6. This value of 6 is also in agreement with the results of photon correlation measurements performed under pulsed excitation on this same QD where a Purcell effect larger than 3.4 is inferred.[16]

Figure 3 shows the results of time correlated single photon counting experiments[17] performed on another QD 1X transition. These measurements have all been performed in low excitation regime where the decay time corresponds to the lifetime of the 1X transition.[18] Measured similar decay times of 1.7 ns at 4 K and 1.9 ns at 50 K show that when the 1X transition is not coupled to any WGMs its lifetime shows almost no dependence on temperature between 4 and 50 K. Hence, nonradiative recombination does not significantly affect the dynamics of the 1X transition within this temperature range.

In summary, we have demonstrated temperature tuning of a single self-assembled InAs QD 1X transition into resonance with a high-*Q* WGM as a useful spectroscopic tool in investigating cavity-QED effects for QDs embedded in three-dimensional optical microcavities. Using photon correlation measurements and time correlated single photon counting measurements we have observed the Purcell effect due to the weak coupling between the QD 1X transition and the WGM. These results constitute an important step towards the realization of efficient single photon sources and strong coupling cavity-QED in semiconductor nanostructures.

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