Polarization control of quantum dot single-photon sources via a dipole-dependent Purcell effect

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We study single photon emission from excitons confined in single InAs quantum dots in elliptical pillar microcavities, demonstrating a polarization dependence of the Purcell effect. The enhancement of the radiative decay rate and emission intensity differs for the two components of the exciton doublet, suggesting each exciton state corresponds to a well-defined dipole direction in the sample plane. This allows the linear polarization of the single photon source to be selected between orthogonal directions by tuning the exciton emission energy between different polarization modes of the cavity.

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Much interest surrounds the use of quantum dot based single photon sources in quantum information processing and quantum communication. For many of the proposed applications the polarizations of the emitted photons are of importance. For example in quantum cryptography[1] or linear optics quantum computing[2] polarization is often used to encode the qubit information. Even for systems using other encoding methods, polarization control is often of great importance due to the birefringence of the components used. Previous studies have shown that the emission of the exciton state of the quantum dot consists of a doublet, the components of which are orthogonally linearly polarized.[3,4] This splitting is believed to be derive from a difference in the electron-hole exchange interaction for the two exciton states due to an asymmetry in the shape and strain within the dot.[4–6] We show here the selective enhancement of one of the two components of the exciton doublet using elliptical microcavities. In addition, tuning the exciton emission energy, by varying the sample temperature, allows the single photon state to be selected between vertical and horizontal polarization.

Recently, efficient single photon emission has been realized by incorporating InAs QDs into a pillar microcavity.[7–10] The cavity contains a discrete set of optical modes, which modify the emission properties of the dot[11,12] through an effect first predicted by Purcell in 1946.[13] As a result of an increase in the optical density of states at the transition energy the spontaneous emission (SE) rate of the QD is increased and photons are preferentially emitted into the cavity mode. With appropriate design this cavity mode can be efficiently collected by a lens. Experiments have shown that the measured enhancement in decay rate of the excitonic state, due to the Purcell effect, is often lower than the calculated value. Cited reasons for this include a mismatch in spatial position and direction of the exciton dipole with the electric field of the cavity mode.[7,9,14]

In contrast to circular pillars, where the fundamental cavity mode (HE_{11}) is polarization degenerate, elliptical pillars display two optical modes with orthogonal linear polarizations aligned with the major and minor axes of the pillar. Previous work on deliberately or accidentally elliptical pillar microcavities has shown that the exciton emission is linearly polarized along the pillar axes.[7,9,15] However, to our knowledge no one has explicitly studied the effect of the nondegenerate cavity modes on the polarized exciton emission. Elsewhere, it has been assumed the electric dipole of the dot is randomly polarized in the sample plane.[7,14] Our experiments show that the dipole is in fact oriented along precise crystallographic directions, allowing careful optimization of the alignment of the exciton dipole and the cavity field.

The enhancement, F, in the spontaneous emission rate due to the cavity, $1/\tau_{cav}$, compared to the free space rate $1/\tau_{free}$ is[14]

$$F = \frac{\tau_{free}}{\tau_{cav}} = F_p \,.\, f(\Delta) \,.\, \frac{|\vec{\varepsilon}(\vec{r})|^2}{|\vec{\varepsilon}_{\max}|^2} \,.\, \left(\frac{\vec{d} \,.\, \vec{\varepsilon}}{|\vec{d}| \,.\, |\vec{\varepsilon}|} \right)^2 . \qquad (1)$$

F_p is a figure of merit for the quality of the cavity and represents the maximum enhancement of the SE rate for a source with zero spectral detuning, and optimal polarization orientation and positioning of the emitter relative to the mode. The second term is a function of the emitter-field spectral detuning (Δ) and the third accounts for the spatial position, r, of the emitter relative to the maximum of the electric field amplitude, ε. The final term accounts for the emitter-field orientation and it is this term that introduces the polarization dependence. For an emitter on resonance (zero detuning) with a particular polarized cavity mode this term selectively enhances the SE rate of photons of the same polarization.

The samples used for this study were grown by molecular beam epitaxy. Here we concentrate on results from a structure consisting of a GaAs λ-cavity between a 17 period upper and 20 period lower AlAs/GaAs distributed Bragg reflector (DBR) mirror. A layer of low-density InAs/GaAs quantum dots was grown at the center of the cavity. The cavity mode wavelength in a planar section of the wafer is 945 nm. Pillars 4.6 μm deep were fabricated using standard photolithography and a $SiCl_4$ reactive ion etch. They were orientated in one of two ways, such that their major (minor) axis was along the $[1\bar{1}0]$ ($[110]$) direction or visa versa.

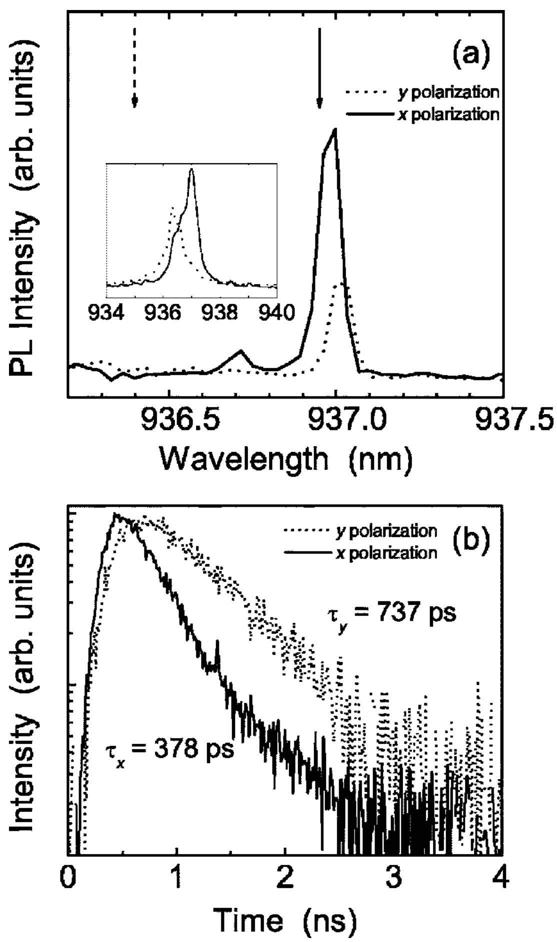

FIG. 1. Polarized μPL from pillar A. (a) An exciton doublet, on resonance with the x polarized cavity mode, has different intensities for the x- and y-polarized emission. The solid (dashed) arrow marks the positions of the $x(y)$ polarized cavity mode. Inset: high excitation density μPL showing the x- (solid line) and y- (dashed line) polarized cavity modes. (b) Time-resolved measurements for the x- (solid line) and y- (dashed line) polarized exciton states.

Samples were mounted in a continuous flow helium cryostat with a base temperature of 5 K. Micro-photoluminescence (μPL) was excited using a mode-locked pulsed laser operating above the GaAs bandgap and well outside the DBR stopband. The laser was focused to a 2 μm spot on the sample surface using a microscope objective with numerical aperture=0.5. Luminescence was collected with the same objective and passed through a monochromator to either a charge-coupled device for spectral analysis or an avalanche photo diode (APD) for time-resolved measurements. The time resolution of the set up is 180 ps. All results have been normalized to take account of the polarization dependence of the transmission of our system.

The results presented here are for pillars with a 3.0μm major axis and a 1.5μm minor axis. Pillar A has the major axis orientated along the $[110]$ (x) direction and minor axis along the $[1\bar{1}0]$ (y) direction. Under strong excitation the nondegenerate cavity modes can clearly be seen (inset Fig. 1), with the y-polarized (minor axis) mode blueshifted from the planar cavity mode by more than the x-polarized (major axis) mode. In an elliptical pillar microcavity these modes are nondegenerate due to the requirement by Maxwell's equations for the electric field component parallel to a dielectric boundary to be continuous. This lifts the degeneracy of the two oppositely polarized HE_{11} modes because the spatial distributions, and hence effective refractive indices, of the modes differ. The mode with the electric field parallel to the major axis of the pillar has the smaller blueshift. In this particular pillar the fundamental mode splitting is ~0.9 meV. For pillars with the major (minor) axis along the $y(x)$ direction the mode positions are interchanged. Pillar A has a quality factor, Q, ~2000.

The same pillar contains a single quantum dot on resonance with the x-polarized cavity mode at $\lambda=937$ nm at 5 K. Under weak excitation a single exciton line, identified by the linear dependence of its emission intensity on the excitation power, is visible. Polarization-dependent μPL measurements on these dots show that the exciton is a doublet with linearly polarized emission along the x and y directions. These states of the exciton doublet are split by ~50μeV, with the y-polarized emission to longer wavelength. Figure 1 shows the PL emission from both of the spin states. The x-polarized spin state emission is 2.6 ± 0.1 times brighter than the y-polarized state. In this pillar the x-polarized state is on resonance with the x-polarized cavity mode and is preferentially emitted into this mode. In contrast the y-polarized state cannot couple to the x-polarized cavity mode as the final term in Eq. (1) is zero and only weakly couples to the y-polarized mode as it is detuned by 0.85 nm, emitting instead into modes along the cavity and leaky modes. Also, the cavity mode emission is lobe-like in the far field and is more efficiently collected by the microscope objective than the leaky modes. Time-resolved measurements (inset, Fig. 1) show the $x(y)$-polarized state has a lifetime of 378 ± 3 ps (737 ± 30 ps). A QD far from resonance, thus only coupling to leaky modes, had a measured lifetime of ~1 ns. Therefore we measure an enhancement of $F=2.7\pm0.2$ (1.4 ± 0.1) in the spontaneous emission rate of the QD. This is a clear indication of a polarization dependence to the Purcell effect and enables us to prepare photons in a given state.

Pillar B, also with its major axis along the x direction, had an exciton doublet, $\lambda=936.7$ nm, on resonance with the y-polarized cavity mode at 5 K. Second-order correlation measurements showed single photon emission. Polarized emission was passed through a monochromator and then to two APDs, acting as "start" and "stop" channels, in a Hanbury-Brown and Twiss experimental setup. A typical histogram is shown in Fig. 2. The central peak, at $\tau=0$ s, indicates the probability of detecting a count on both APDs at the same time. This peak has a normalized area of 0.2, a sign of single photon emission, and shows the chance of emitting two or more photons is reduced by a factor of 5 compared to a classical source of the same intensity. The peaks immediately adjacent to the central peak also show a reduced multiphoton probability. This photon antibunching has a characteristic lifetime of 17 ± 4 ns and may be attributed to long-lived charge states of the quantum dot.[16]

Micro-PL emission from the y-polarized exciton state was 2.3 ± 0.1 times brighter than from the x-polarized state [Fig. 3(a)]. Time-resolved measurements show the $y(x)$-polarized

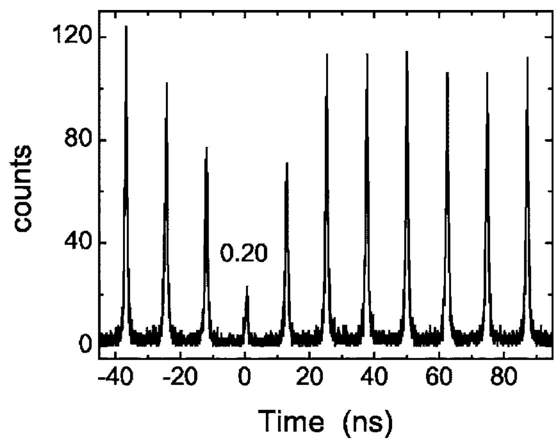

FIG. 2. Typical histogram of the second-order correlation of an exciton on resonance with the higher wavelength cavity mode at 5 K.

state to have a lifetime of 391±7 ps (631±15 ps). These are of similar value but reversed polarization to pillar *A* and confirm that the polarized exciton states and cavity modes are coupling like with like as expected. We are therefore able to select the polarization of the collected photons by placing the emitter in a polarized mode of the cavity.

The emission wavelength of a QD and that of the cavity

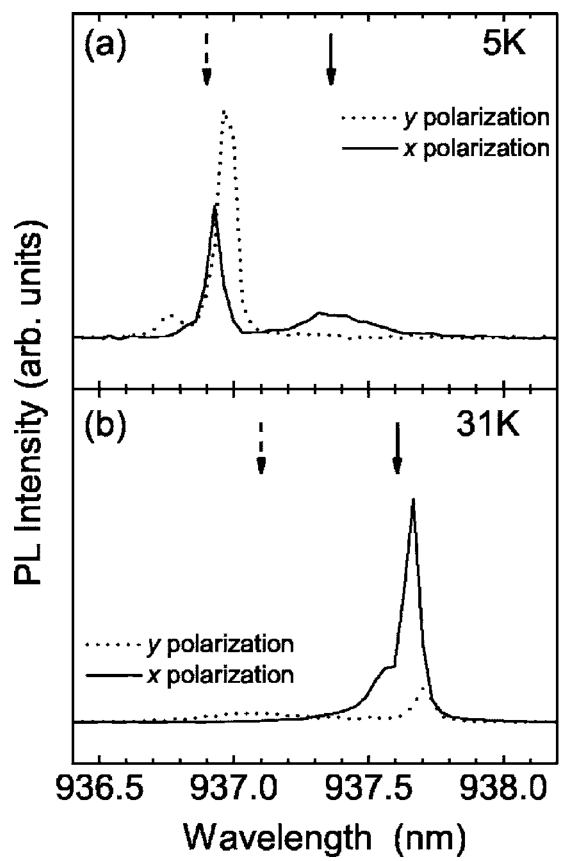

FIG. 3. Temperature-dependent μPL from pillar B, the *x*- (solid line) and *y*-polarized (dashed line) exciton states are on resonance with (a) the *y*-polarized cavity mode (dashed arrow) at 5 K and (b) the *x*-polarized cavity mode (solid arrow) at 31 K.

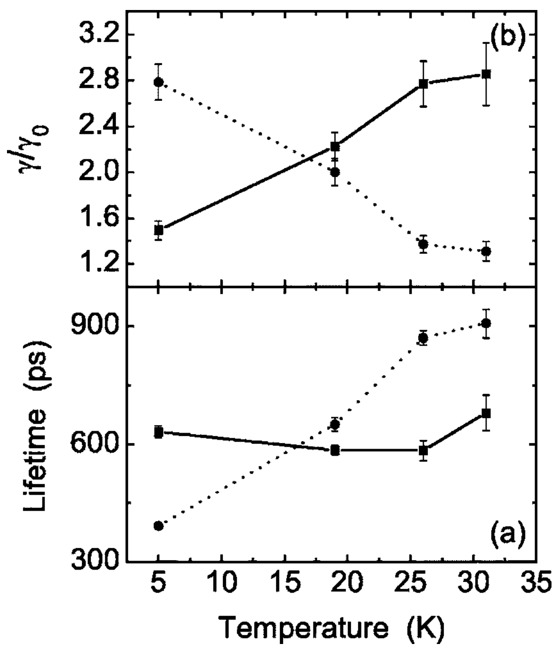

FIG. 4. (a) Temperature-dependent lifetimes of the *x* (solid line) and *y* (dashed line) exciton spin states in pillar B. (b) Spontaneous emission rate enhancement compared to an off-resonance dot.

are both temperature dependent, however the dot wavelength changes faster with temperature than the cavity mode. By increasing the temperature to 31 K we are able to tune the exciton in pillar *B* from on resonance with the lower wavelength mode to on resonance with the higher wavelength (*x*-polarized) mode [Fig. 3(b)]. The *x*-polarized emission is now ~6 times brighter than the *y*-polarized emission and has a shorter radiative lifetime, 680±45 ps compared to 907±36 ps. A small amount of background emission, probably from a continuum of states in the wetting layer, can be seen emitting into the cavity modes. Figure 4(a) shows the lifetimes of the two exciton states as a function of temperature. The crossover, due to the changes in detuning of the two exciton states with their respective cavity modes, occurs at about 17 K. The radiative lifetime of the *x*-polarized exciton state does not appear to decrease, as would be expected from Eq. (1), as it comes onto resonance. However separate measurements on dots far off resonance, which emit only into leaky modes and have similar lifetimes to dots not in a cavity, show that their intrinsic lifetime initially increases with temperature and that an off-resonance dot has a lifetime of ~1.5 ns at 31 K.[17] The enhancement in the SE rate as a function of temperature compared to emission from off-resonance dots is plotted in Fig. 4(b). At 31 K the (*y*)*x*-polarized spin state exhibits an SE rate enhancement of 2.2±0.2 (1.4±0.2).

The polarization of photons from each exciton state depends on the spin state of the exciton; for dots that are not in a cavity there is no preferred polarization of emission indicating an equal probability of occupation for both spin states.[4] The cavity modifies the modes these states can emit into, resulting in a preferential collection of one polarization of photons. However, the larger ratio in the emission intensities of the two polarizations in pillar *B* at 31 K compared to the intensity ratios seen in both pillars at 5 K suggests that we are not just collecting a greater proportion of one polarization but, also, that the total radiative emission is predominantly of that polarization. This may be due to a number of factors including the scattering of the exciton state. Scattering times of the order of the radiative lifetime have been inferred from cross-polarized correlation measurements.[4,6] Also, carrier redistribution in the dot and wetting layer (WL) is more likely at elevated temperatures.[18] Carriers in the longer lived y-polarized spin state of the exciton are more likely to transfer to the WL than carriers in the x-polarized spin state, while the probability of (re)capture into either state remains equal. Both of these mechanisms may lead to an increase in the proportion of emitted photons with the same polarization as the on-resonance cavity mode.

In conclusion, we have demonstrated the selective enhancement of the single photon spontaneous emission rate of a single spin state in an exciton doublet when the exciton is on resonance with, and parallel to, a polarized cavity mode. Using temperature to tune the exciton emission wavelength between cross-polarized cavity modes it is possible to change the spin state that is enhanced, thus changing the sign of the emission polarization. This ability to control the photon polarization could be useful in quantum cryptography or other quantum information processing systems.

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