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Large spontaneous emission enhancement in InAs quantum dots coupled to microdisk whispering gallery modes

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Measuring the enhancement of spontaneous emission decay rates of quantum dot emission coupled to microcavity modes is typically hampered by variable coupling of the quantum dot emission. This is particularly evident in the microdisk cavity since the whispering gallery modes are localized near the disk edge, while quantum dot emitters are typically uniformily distributed throughout the disk. The distribution of spontaneous emission decay rates under these circumstances can be determined using a distribution function for the various spontaneous decay rates, and demonstrate that large decay rate enhancement are present. To remove the spatial coupling variation, quantum dots are selectively placed near the microdisk edge. Initial photoluminescence measurements indicate that recombination processes in these quantum dots are not dominated by surface recombination.

1 Introduction The modification of spontaneous emission of an emitter in the presence of a cavity has been known since Purcell's work in the mid 1940's. If an ideal emitter is spatially and spectrally aligned with a mode in the an electromagnetic cavity, its spontaneous emission rate is enhanced by the Purcell factor $F_p = 3Q(\lambda/n)^3/4\pi^2V$, where Q is the cavity quality factor, V is the effective mode volume, λ is the emission wavelength, and n is the index of refraction. Thus, to obtain a large enhancement, a cavity with small mode volume and high quality factor is desired. This has been achieved in semiconductor systems using microcavities. For example, micropost cavities, formed by the etching of planar, distributive-Bragg reflector (DBR) based vertical cavities can have very small mode volumes, but often suffer from small cavity quality factors as the post diameter becomes small. A different type of cavity, the microdisk cavity, have substantially higher Q. Since the microdisk contains whispering gallery modes formed by total internal reflection at the boundary of a disk, the mode exists near the disk perimeter, and the mode volume is typically larger than the micropost. Nevertheless, if the disks can be made small the mode volume can be reduced and the enhancement factor can be large. For example, for a whispering gallery mode of $Q = 12000$ in a 1.8 μm diameter disk at $\lambda = 1$ μm, the Purcell factor is calculated to be 190 [1].

The emitter is of course not benign in this process. The above calculation assumes the emitter has a homogeneous linewidth that is equal to or smaller than the cavity. The InAs quantum dots (QDs) formed lattice mismatch strain in GaAs meet this criteria, having spectral linewidths on the order of

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10–100 μeV, well below the cavity linewidth of a cavity with Q = 20000. In addition, they can be inserted directly into the epitaxial growth process used to form the cavity structure.

However, the spontaneous emission rate enhancements measured in microdisk cavities containing InAs QD emitters is not nearly as good as theory, nor as good as the measured mode volume and quality factors would indicate. The reduced enhancements of the spontaneous emission decay are the result of the large inhomogeneous spectral broadening of quantum dot energy levels due to size fluctuations and environmental variations, and the random spatial distribution of quantum dots in a microdisk. In the initially assumption, perfect spatial and spectral alignment was assumed, but the situation here is far from this ideal case.

2 Results and discussion While these InAs QDs have discrete energy levels and narrow linewidths there are size, shape and environmental variations that lead to spectral linewidths of 10 s of meV. Furthermore, the QDs are approximately uniformly distributed over the cavity region, and the whispering gallery modes are maximum near the disk edge.

The coupling of an emitter to a cavity mode depends both on the spectral matching of the emitter emission line to the cavity mode frequency, and on the spatial overlap of the emitter with the mode. More specifically [2],

$$\frac{\gamma}{\gamma_0} = \frac{3Q(\lambda_c/n)^3}{4\pi^2 V} \frac{\Delta\lambda_c^{\;2}}{4(\lambda-\lambda_c)^2+\Delta\lambda_c^{\;2}} \frac{|E(r)|^2}{|E_m|^2} 2\eta^2 \tag{1}$$

where γ_0 is the spontaneous emission rate of the quantum dot without the cavity; λ is the quantum dot emission wavelength; λ_c and $\Delta\lambda_c$ are the central wavelength and the linewidth of the whispering gallery mode, respectively; $E(r)$ is the electric field amplitude of the whispering gallery mode at the position of the quantum dot; $E_m = (h\nu/2\varepsilon_0 n^2 V)^{1/2}$. The first term F_p in Eq. (1) is the Purcell factor. The second term and the third term describe the spectral and spatial matching between the QD and the cavity mode. The factor of 2 comes from the two-fold degeneracy of the whispering gallery mode and η describes the orientation match between the dipole of the quantum dot and the polarization of the cavity mode. Despite the large value of the Purcell factor, the spectral, spatial, and orientation mismatches lead to a significant reduction of the enhancement factor. Assuming uniform distribution of quantum dots in space and in the wavelength spectrum, the average enhancement factor is

$$\left\langle \frac{\gamma}{\gamma_0} \right\rangle = F_p \left(\frac{1}{2\,\Delta\lambda_c} \int_{-\Delta\lambda_c}^{\Delta\lambda_c} \frac{\Delta\lambda_c^{\;2}}{4(\lambda-\lambda_c)^2+\Delta\lambda_c^{\;2}}\,\mathrm{d}\lambda \right) \left(\frac{1}{V} \int |f(r)|^2\,\mathrm{d}r \right) 2\,\frac{1}{3} \quad , \tag{2}$$

where $f(r)$ is the envelop function of the electric field amplitude of the whispering gallery mode, and its norm is unity at the antinode of the electric field. The average enhancement factor is about 10 times smaller than the Purcell factor [3].

Because the spontaneous emission enhancement factor depends on the spectral and spatial overlap of each QD with the whispering gallery mode, each QD in the microdisk undergoes a specific spontaneous emission rate enhancement. To extracted the distribution of spontaneous emission rates from the temporal decay of the QD emission intensity, we have determined the distribution of the spontaneous emission rates. The off-resonance distribution function is a narrow peak centered at ~2 GHz, representing the uniform isotropic spontaneous emission rate. Here, the central decay rate corresponds to a decay time of 500 ps, which is approximately the decay time in QDs in our non-processed samples. The on-resonance distribution function has a long tail at the higher decay rate, indicating that the decay rates for some QDs are enhanced by the weak-cavity coupling. The spontaneous emission rates for some QDs exceed 20 GHz, corresponding to decay times of less than 50 ps. Thus, for the quantum dots with good spatial and spectral coupling to the cavity mode, the enhancement of their spontaneous emission rates does exceed 10 as predicted; however, most of the QDs are not perfectly matched and the average enhancement is much lower.

The Purcell effect of a single InAs QD in a GaAs microdisk was studied [4]. However, although the frequency of the single quantum dot can be tuned into resonance with a whispering gallery mode by adjusting the sample temperature, its location in the microdisk is random and of course cannot be adjusted. Thus, in general, to observe such effects chance alignments must occur. Here, we show the selectively growth and ordering of QDs near the edge of microdisks. We believe this technique will allow us to achieve good spatial overlap between the QD emitters and the whispering gallery modes. The technique used to selectively located QDs at the microdisk edge is based on molecular-beam epitaxy (MBE) regrowth of the QD layer and upper cavity structure of the microdisk. In this process, the deposition of the InAs QD layer occurs after the microdisk has been defined. After a GaAs buffer layer, a 500 nm thick $Al_{0.7}Ga_{0.3}As$ is deposited, followed by an approximately 80 nm thick GaAs layer. The sample is removed from the growth chamber and the microdisks are defined by optical lithography with diameters ranging from 3 µm to 50 µm. A two-step wet etching process is used to define the microposts. In the process approximately 30 nm of the top GaAs has been etched away. Returning the sample to the MBE system, a thin GaAs buffer layer, the InAs QDs layer, and the upper cavity region are deposited.

In Fig. 1, atomic-force microscopy (AFM) images of the surface distribution of InAs QDs on a 7 µm diameter microdisk are shown. In these images the QD layer is deposited and the crystal growth terminated, leaving the QDs exposed on the surface for AFM imaging. Furthermore, in Fig. 1a, AlGaAs layer and thus the undercut is not present. In Fig. 1a InAs islands are aligned at the edge of the microdisk structure. In addition, InAs islands are also shown at the bottom of the post, on the lower GaAs region. The In adatoms diffuse on the surface of the microdisk to the disk edge because the free surface provides an increased strain relaxation. In Fig. 1b, InAs island formation is shown at the edge of a full microdisk structure (including the AlGaAs layer and the undercut processing). The rough edge of the microdisk is a result of the processing. Clear alignment of InAs islands at the disk edge is visible. In this sample, the islands are approximately 80 nm from the disk edge.

Because the InAs islands are close to the disk edge there is a concern that nonradiative surface recombination will dominate the decay process. Initial 4 K photoluminescence measurements are shown in Fig. 2. The emission at 850 nm in Fig. 2a is due to the QW-like wetting layer and is present through the disk. The emission at longer wavelengths is due to QDs localized near the whispering gallery modes of the cavity. In Fig. 2b, cavity modes are shown, where broad QD emission is filtered through the modes.

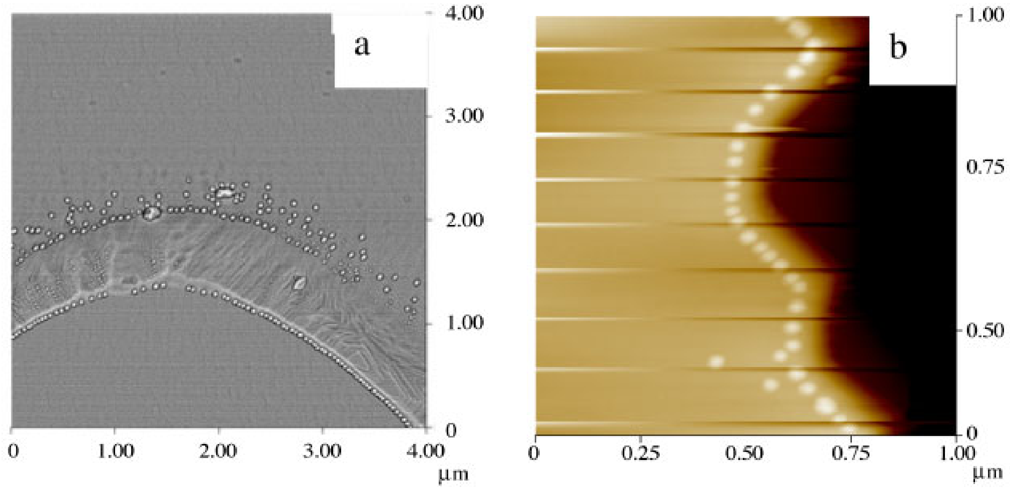

Fig. 1 (online colour at: www.interscience.wiley.com) Atomic-force microscope (AFM) images 7 µm diameter post a), and disk b) structures. In both images InAs islands preferentially align at the post or disk edge.

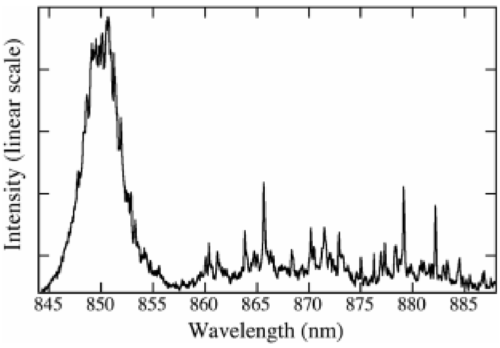

Fig. 2 4 K photoluminescence of a 7 μm diameter microdisk with QDs selectively regrown near the disk edge.

3 Conclusions We have shown that in microdisk cavities with a random distribution of QDs, most of the QD emitters are not spatially coupled to the whispering gallery modes, and thus the full cavity enhancement on the spontaneous emission decay is not observed. By regrowth of InAs QDs we have selectively positioned QDs at the microdisk edge, directly in the cavity mode. Low temperature PL indicate the QDs are optically active, and thus this method is promising to increase the average decay rate in optical devices utilizes ensembles of QDs, and will add in single QD experiments.

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