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An efficient source of single photons: a single quantum dot in a micropost microcavity

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Abstract

We have used a single quantum dot in a micropost microcavity to generate triggered single photons. Coupling between the quantum-dot dipole and the confined microcavity mode leads to a large enhancement of the spontaneous emission rate. This, in turn, leads to efficient coupling of the emitted photons into a single traveling-wave mode. Optimization of the microcavity design should lead to nearly unity efficiency, and could also allow for strong coupling and for single-dot lasing.

Keywords: Quantum dots; Microcavities; Single photons

Single photons are currently in demand, particularly for application to quantum cryptography and linear-optical quantum computation [1,2]. Semiconductor quantum dots (QDs) are particularly interesting for the production of single photons [3,4]. The energy of the photon emitted due to electron-hole recombination in a dot is uniquely determined by the total charge configuration of the dot [5]. If we excite a QD with a laser pulse and create several electron–hole pairs in the dot, then, it is possible to spectrally isolate the single photon emitted by recombination of the last electron–hole pair [6].

QDs offer several advantages as sources for single photons. They have large oscillator strengths, narrow spectral linewidths, high photon yield, and excellent long-term stability. The materials used to make QDs are compatible with mature semiconductor technologies, allowing them to be further developed and integrated with other components. The usefulness of most QD single-photon sources, though, is limited by their low efficiencies. The dots radiate primarily into the high-index substrates in which they are embedded, and very few of the emitted photons can be collected. We increase the source efficiency by placing a dot inside a microscopic optical cavity, thereby enhancing its spontaneous emission rate into the cavity mode. Perhaps the most practical microcavities for this purpose are microscopic posts etched out of distributed-Bragg reflector (DBR) microcavities [7,8]. Light escaping from the fundamental mode of a micropost microcavity is well approximated by a Gaussian beam, and can thus be efficiently coupled into optical fibers, detectors, or other downstream optical components.

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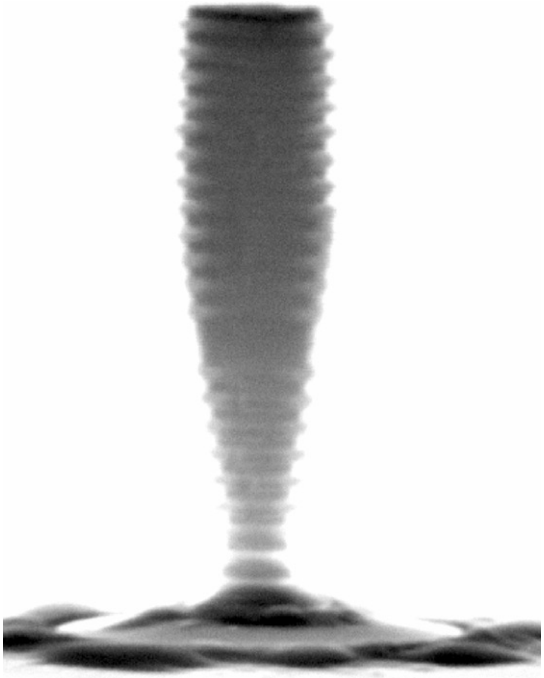

Fig. 1. Scanning-electron microscope image of a micropost microcavity with a top diameter of 0.6 μm and a height of 4.2 μm.

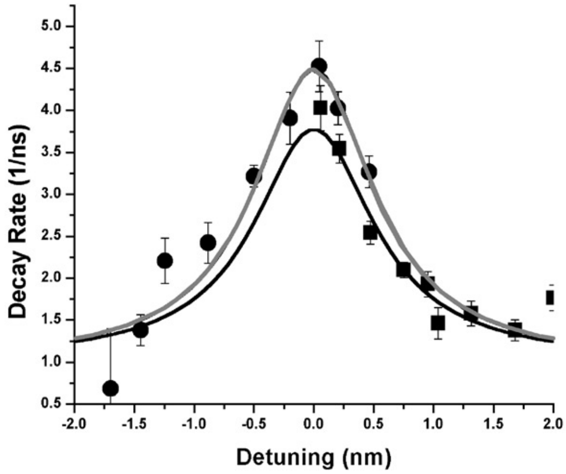

Fig. 2. Measured lifetimes of two quantum dots as a function of temperature-dependent detuning from a micropost microcavity resonance (squares for one dot, circles for the other), as well as Lorentzian fits (lines).

We produce quantum dots by strain-induced self-assembly during molecular-beam epitaxy (MBE) of InAs on GaAs [9]. The planar microcavity is made by depositing GaAs/AlAs DBRs above and below the quantum-dot layer during the MBE growth, separated by a one-wavelength-thick spacer layer of GaAs. A sub-micron post is etched into the sample using an electron-cyclotron-resonance plasma. Fig. 1 shows a scanning-electron microscope image of a typical micropost. The etch isolates one quantum dot from the ensemble, and also confines light in the lateral direction by total internal reflection (TIR). A single QD is thus coupled to a single three-dimensionally confined optical mode.

In order to verify this coupling, we measured the recombination rate for two QDs in a particular micropost. Pulsed laser light with a photon energy larger than the GaAs bandgap was directed towards the micropost. The sample was held in a liquid-helium cryostat, so that the created carriers were rapidly trapped by the QD, and quickly relaxed to the lowest-energy confined states. Emission was collected by a lens in front of the cryostat, and was filtered spectrally and spatially to eliminate scattered pump light. The light was directed towards a streak camera, which measured intensity as a function of time after excitation. More details on lifetime measurements are given in Ref. [10].

We tuned the emission wavelength of the dots through the cavity resonance by changing the temperature of the sample. Results are shown in Fig. 2. Lorentzian fits give maximum emission-rate enhancement factors of 3.2 ± 0.4 and 2.9 ± 0.2. The difference between the two factors is attributable to different radial positions of the dots in the post.

We have thus clearly demonstrated coupling of single QDs to a single mode of a micropost microcavity. When a QD is resonant with the mode, the majority of the photons from the dot are emitted into the mode. Most of these photons subsequently escape into a single-mode traveling wave. We should thus be able to use such a structure as an efficient source of single photons.

Single photons were generated using a single QD in a micropost microcavity etched from a different MBE-grown sample. Light from the QD was spectrally filtered and analyzed by a Hanbury Brown and Twiss-type apparatus, which records a histogram of time intervals between photons [11]. In the limit of

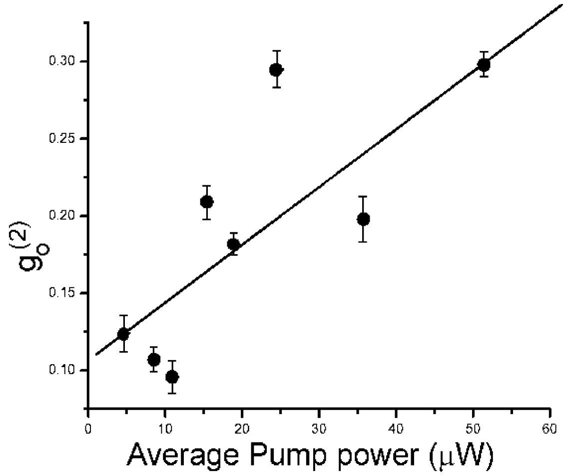

Fig. 3. Area of the central peak in the measured autocorrelation function for photons emitted by a single quantum dot in a micropost microcavity, relative to the area of the side peaks as a function of pump power (points), as well as a linear fit (line).

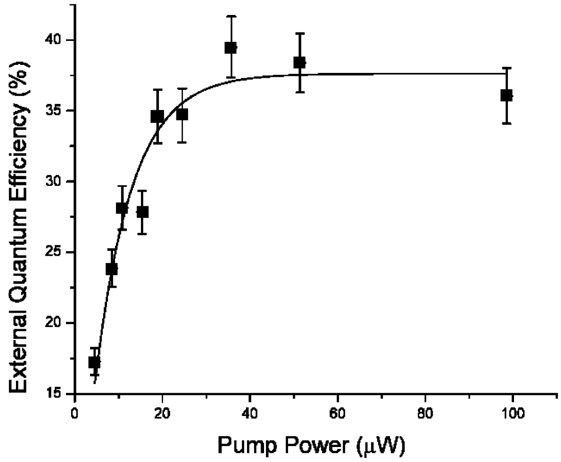

Fig. 4. Measured external quantum efficiency of single-photon generation using a single quantum dot in a micropost microcavity as a function of pump power (points), together with a saturation fit (line).

low total collection and detection efficiency, this histogram approximates the photon autocorrelation function $g^{(2)}(\tau)$. More detail on correlation measurements can be found in Ref. [4].

The measured correlation functions consist of a series of peaks separated by the repetition rate of the excitation laser. Each peak is a two-sided exponential, with a decay constant given by the combination of the spontaneous decay time and the instrument response time. A fit using experimentally determined time constants was used to obtain the ratio $g_o^{(2)}$ of the area of the zero-delay peak to the area of the other peaks. The value of $g_o^{(2)}$ sets an upper bound on the probability of having more than one photon in a given pulse, compared to light with Poissonian photon statistics. Measured values for various pump powers are shown in Fig. 3.

The overall detection efficiency after the initial collection lens was determined by scattering attenuated laser light off the micropost, and comparing the total photon count rate to the optical power measured immediately after the collection lens. The fraction of light captured by the initial lens was estimated using Gaussian-beam optics, and verified by calculations using the finite-difference time-domain (FDTD) method (see Ref. [12] for details). The total photon count rate was normalized by the laser repetition rate and then divided by the collection and detection efficiencies, giving the mean photon number per pulse. We then use the measured multi-photon probability in order to determine the efficiency. Results are shown in Fig. 4. The saturated efficiency is equal to $37.6 \pm 1.1\%$, which is nearly two orders of magnitude higher than for a quantum dot in bulk GaAs.

The efficiency is limited by the relatively low quality factor Q of the microcavity resonance. FDTD simulations show that the difference between Q for the micropost and for the planar microcavity is due to the taper in the micropost diameter. More vertical sidewall profiles, and thus higher efficiencies, should be achievable using different etching techniques, such as chemically assisted ion-beam etching.

Optimization of the microcavity design can increase the quality factor yet further [13]. The rule of thumb generally used for designing microposts is to make mirror layers one-quarter wavelength thick, and to make the spacer layer one wavelength thick. Although this is optimal for a planar microcavity, it does not necessarily lead to the highest Qs for small cavity diameters D. Two factors reduce Q for small D. First, the cavity-mode wavelength blue-shifts away from the center wavelength for the planar cavity, so that the mode is less well-confined in the longitudinal direction. As well, the cavity mode becomes more strongly localized in real space, and consequently less localized in Fourier space (i.e., it consists of a wider range of wave-vector components). Some of these components are not confined in the post by TIR, leading to increased loss in the transverse direction.

We can reduce this transverse loss by tuning the thickness of the cavity spacer layer, thereby delocalizing the mode in real space. We can also relax the mode in the longitudinal direction by reducing the refractive-index contrast in the DBRs. Using these approaches, we were able to achieve Q as high as 10^4 together with a mode volume as small as 1.6 cubic optical wavelengths. This would mean an efficiency of nearly 100% for a single-photon source.

It would also mean a vacuum Rabi frequency of 224 GHz, which is significantly larger than the typical QD homogeneous linewidth of 20 GHz. Strong coupling between the QD dipole and the cavity mode should thus be possible. Finally, laser action should be possible using the single QD as an active medium. If we assume a typical lifetime without a cavity of 0.5 ns, lifetime reduction to less than 5 ps should be possible in optimized microposts. This is less than the photon storage time in the cavity of 5.3 ps, so that the quantum laser threshold can be reached [14].

We have demonstrated strong enhancement of the spontaneous emission rate of single quantum dots coupled to a single mode in a micropost microcavity. This has allowed us to demonstrate efficient generation of single photons. The observed external quantum efficiency is 37%, nearly two orders of magnitude higher than for a quantum dot in bulk semiconductor material. At the same time, the probability of having more than one photon in a given pulse is reduced by a factor of seven as compared to Poissonian light. We have also used first-principles simulations to optimize the design of the microcavities. Calculated quality factors as high as 10^4 were predicted, together with mode volumes as low as 1.6 cubic optical wavelengths.

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References

[1] W. Knill, R. Laflanne, G.J. Milburn, Nature 79 (2001) 46.
[2] G. Brassard, N. Lütkenhaus, T. Mor, B.C. Sanders, Phys. Rev. Lett. 85 (2000) 1330.
[3] P. Michler, et al., Science 290 (2000) 2282.
[4] C. Santori, et al., Phys. Rev. Lett. 86 (2001) 1502.
[5] L. Landin, et al., Science 280 (1998) 262.
[6] J.-M. Gérard, B. Gayral, J. Lightwave Technol. 17 (1999) 262.
[7] J.-M. Gérard, et al., Phys. Rev. Lett. 81 (1998) 1110.
[8] G.S. Solomon, M. Pelton, Y. Yamamoto, Phys. Rev. Lett. 86 (2001) 3903.
[9] D. Bimberg, M. Grundmann, N.N. Ledentsov, Quantum Dot Heterostructures, Wiley, Chichester, 1999.
[10] C. Santori, G.S. Solomon, M. Pelton, Y. Yamamoto, Phys. Rev. B 65 (2002) 073310.
[11] R. Hanbury-Brown, R.Q. Twiss, Nature 178 (1956) 1447.
[12] M. Pelton, J. Vučković, G.S. Solomon, A. Scherer, Y. Yamamoto, IEEE J. Quantum Electron. 38 (2002) 170.
[13] J. Vučković, M. Pelton, A. Scherer, Y. Yamamoto, Phys. Rev. A 66 (2002) 023808.
[14] M. Pelton, Y. Yamamoto, Phys. Rev. A 59 (1999) 2418.