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Experiments Versus Modelling in Quantum Dot Pillar Microcavities

J.G. Rarity, Y.-L.D. Ho, R. Gibson, C.Y. Hu, M.J. Cryan, I.J. Craddock, C.J. Railton, D. Sanvitto*
A. Darei*, M. Hopkinson*, J.A. Timpson*, A.M. Fox*, and M.S. Skolnick*
Department of Electrical & Electronic Engineering, University of Bristol, BS8 1UB, UK
** Department of Physics, University of Sheffield, Sheffield S3 7RH, UK*
Tel: 44(0)1179545646, Fax: 44(0)1179545206, e-mail:John.Rarity@bristol.ac.uk

ABSTRACT

Recently, single photon sources have been realised by coupling InAs quantum-dots into circular micro-pillar microcavities based on distributed Bragg reflectors (DBRs). These sources can be highly efficient because the high semiconductor refractive index collects a large fraction of the spontaneous emission into the waveguide mode. We have modelled emission from circular, square, elliptical and rectangular pillars using the finite difference time domain (FDTD) method and see enhanced emission into the cavity mode and improved efficiency for coupling light out of the microcavity. The cavity *Q*-factors can be very high even when the pillar diameter (dimension) is comparable to the emission wavelength. In the elliptical and rectangular cavities the modes separate (in frequency) into a high-*Q* resonance with polarisation parallel to the long axis and a lower *Q*-factor resonance with polarisation orthogonal to the long axis. We compare our modelling with preliminary measurements made on micro-pillar microcavity samples containing a layer of low density InAs dots at the cavity centre.

Keywords: Bragg reflection, cavity quantum electrodynamics, light confinement, optical microcavities, quantum dots, spontaneous emission modification.

1. INTRODUCTION

Sources emitting one photon at a time are required for applications in quantum communication [1] and quantum computation [2]. Single photon sources based on self-assembled quantum dots (QDs) are a promising candidate showing no bleaching effects, long-term stability, high repetition rate (short lifetime), and compatibility with standard semiconductor processing techniques. These highly efficient single-photon sources can be significantly improved by coupling the QDs into a resonant cavity mode of a micro-pillar microcavity. Such cavities can be grown using Ш-V semiconductor materials. The non-classical light emitted by a single dot on resonance is efficiently collected into the cavity mode and escapes preferentially from the top of the pillar making an efficient single-photon source [3-5]. For quantum information applications, polarization mode control of single-photon sources is important to allow encoding in polarisation and to avoid birefringence in the optical components. Hence we consider the polarisation control of single-photon emitters in pillar microcavities and study the electromagnetic field distribution by changing the cross-section from circular (square) to elliptical (rectangular) [6]. We aim to design a highly efficient polarised single-photon source with large Purcell factors (F_p) [4, 5].

2. GEOMETRIES OF CIRCULAR (SQUARE) AND ELLIPTICAL (RECTANGULAR) MICRO-PILLAR MICROCAVITIES

The 3-D finite difference time domain (FDTD) method has been used to analyze circular, square, elliptical and rectangular micro-pillar microcavities. In these microcavities the mirrors are distributed Bragg reflectors (DBR) made from alternating quarter wave layers of high (GaAs) and low (GaAlAs) refractive index material (see Fig. 1). Furthermore, the sample was grown by molecular beam epitaxy (MBE) and the planar cavity consists of a GaAs λ-cavity with a 27 pair DBR lower mirror and a 20 DBR pair upper mirror, resonating at a wavelength close to 0.96 μm (for large pillar diameter). The active layer is made up of InAs self-assembled QDs grown in the centre of the GaAs cavity. For these microcavity structures, three-dimensional optical confinement is thus achieved by combining the vertical confinement of the photons by the DBR mirrors with the lateral confinement provided by the large refractive index contrast at the smooth etched sidewalls. The high Q-factor of the resonant cavity mode further enhances the emission rate into the mode and such structures thus efficiently couple the light into the fundamental guided mode of the pillar microcavity.

The fabrication of square and rectangular micro-pillars is achieved by employing a focused ion beam etching equipment using 30 keV Gallium ions. Initial measurements indicated that this etching method is rather aggressive. Consequently we have subsequently reduced the flux of Gallium in our final etching steps by around 50-100 times using gas-assisted etching (GAE) with a low concentration of iodine.

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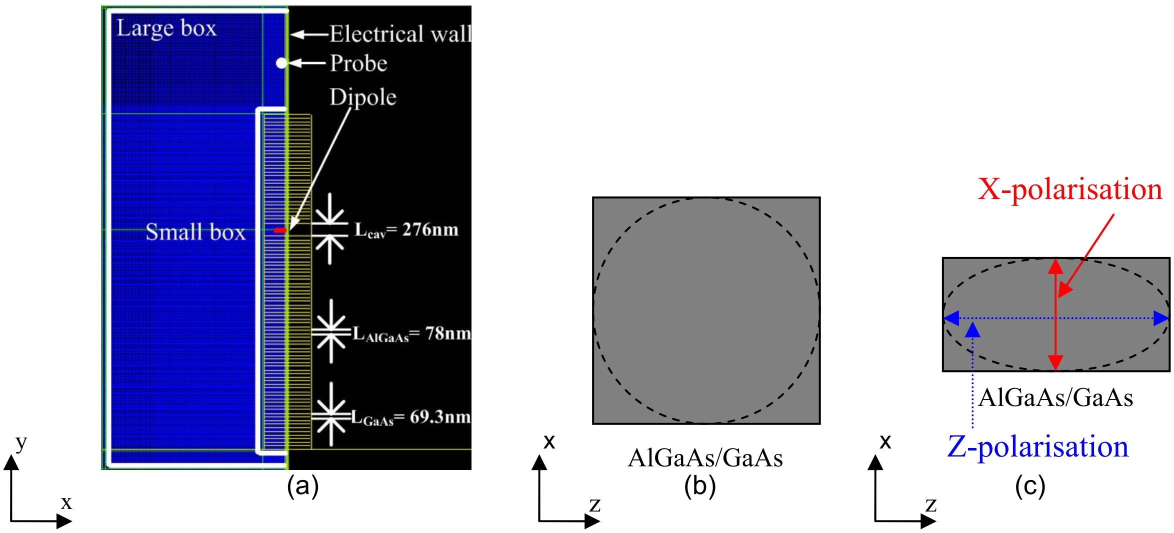


(a) (b) (c)

Figure 1. (a) Y-X plane of device showing the mesh, electrical wall, probes, dipole, cavity thickness (L_{cav}), and DBR periodicity (L_{AlGaAs}, L_{GaAs}). (b),(c) are the top view of circular (square) and elliptical (rectangular) pillars.(c) also illustrates the x-polarization (red solid line) and z- polarization (blue dashed line).

3. MODELLING AND EXPERIMENTS OF THE POLARISATION MODE CONTROL IN QUANTUM DOT PILLAR MICROCAVITIES

Here, we will concentrate on the modelling and experimental results from rectangular pillar with a 1.5 µm major axis (z-polarisation) and the 0.6 µm, 0.8 µm, 1.0 µm minor axis (x-polarisation) respectively and a 1.5 µm for square pillars.

3.1 3-D FDTD modelling of the pillar microcavities

For 3-D FDTD modelling of the pillar microcavities, we place a broad band Ex-dipole source in the centre of the microcavity and input a short few-cycle excitation pulse to model the emission from the quantum dot [7]. The cavity then rings at its resonant frequency and we monitor this using a probe above the pillar. Taking the Fourier transform of the ringdown signal (in time) allows us to determine the resonant frequencies of the cavity and also to an estimate the Q-factor ($Q = \lambda / \Delta\lambda$) as shown in Fig. 2. We then focus solely on the cavity resonant frequency to plot electric field distributions in Fig. 3 and can estimate the light collection efficiency and enhancement into the cavity mode (the Purcell factor).

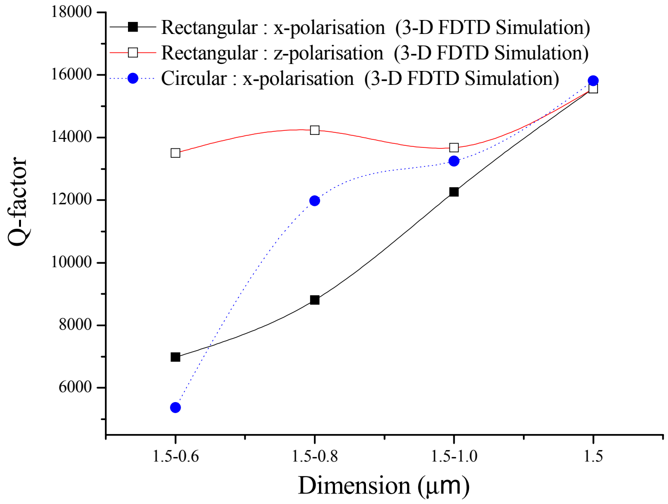
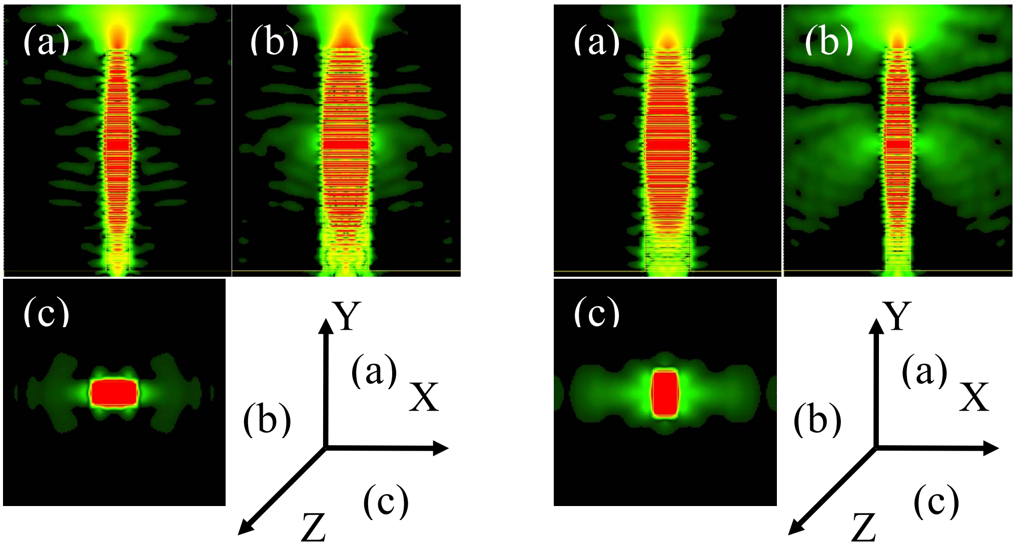


Figure 2. Q-factors of the fundamental HE_{11} modes of a 1.5 µm major axis (z-polarisation) and the 0.6 µm, 0.8 µm, 1.0 µm minor axis (x-polarisation) respectively and a 1.5µm square pillar the structure of 20 DBR pairs on top and 27 pairs on bottom calculated by the FDTD method.). Also illustrates the data for the x-polarisation of elliptical pillars (blue point). Calculation of the z-polarisation Q-factors for elliptical pillars are ongoing .



(a) (b)

Figure 3. FDTD calculation of the single frequency 'snapshot 'of (a) x-polarization, and (b) z-polarization of rectangular pillar (1.5 μm major axis and the 0.8 μm minor axis), for each plane are in the fundamental HE_{11} *mode.*

3.2 Experimental results of the pillar microcavities

For measuring the *Q*-factor and antibunching, we combined a low-temperature micro-photoluminescence (μ-PL) equipment with a Hanbury-Brown. Twiss type (HBT) apparatus [8]. Individual quantum dot emission can be isolated in wavelength scale micro-pillars pumped by a Ti:Sapphire laser with lower power, and also can be tuned in and out of resonance by changing the temperature. Here we have been able to see individual dots in our 1.5 and 2.0 μm square pillars. We show a spectrum with quantum dots off resonance with the cavity mode (wavelength of 932 nm) at a temperature of 4.3 K in Fig. 4. Short wavelength dots can be tuned into resonance with the cavity by increasing temperature as shown in Fig 5. For 2.0 μm square pillar, with increasing pump power, the single QD emission turns saturated, and the cavity mode intensity develops. Despite the high background from the cavity we still see some antibunching in our HBT measurement in Fig. 5*b* as evidenced by the suppressed central coincidence peak.

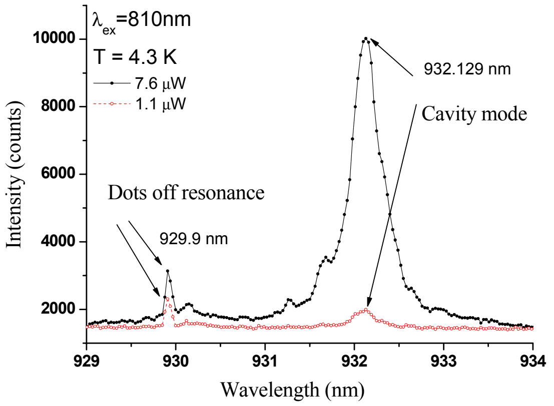
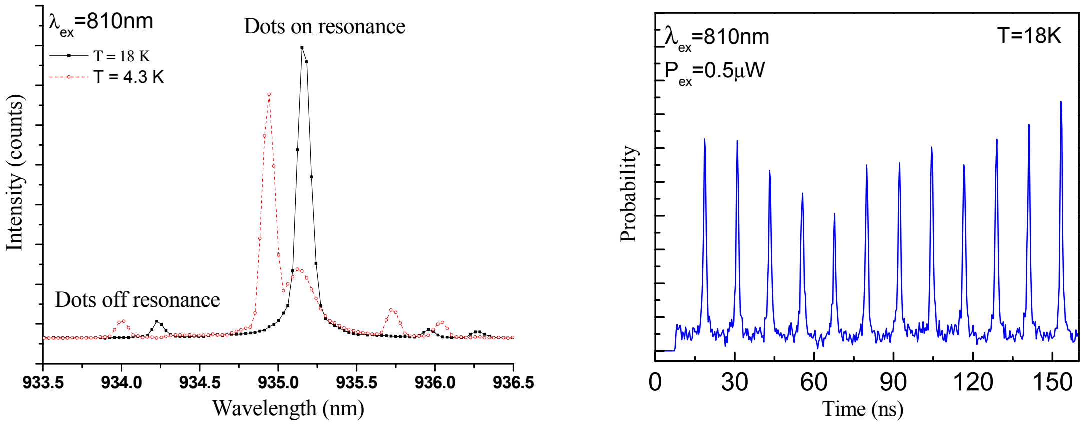


Figure 4. μ -PL spectrum of a 1.5 μm square micropillar excited at $\lambda = 810$ *nm and power* $P = 1.1$ *μW (dotted line) and 7.6 μW (solid line) at a temperature of 4.3 K where a quantum dot is on- and off-resonance with the cavity mode at a wavelength of 932 nm.*



(a) (b)

Figure 5. μ -PL spectrum of a 2 μm square micro-pillar excited at λ = 810 nm and a temperature of T = 4.3 K (dotted line) and 18 K (solid line) where a quantum dot is on- and off-resonance with the cavity mode at a wavelength of 935 nm. (b) Measured second order correlation function for emission from the quantum dot.

4. CONCLUSIONS

We have modelled micropillar microcavities containing single quantum dots using the FDTD method and have seen high cavity *Q*-factors in circular, square, rectangular and elliptical microcavities. In rectangular and elliptical cavities the cavity modes are split into two polarisation modes. One of the modes maintains high *Q*-factor down to smaller mode volumes.

We have also measured cavity mode spectra and spectra of individual quantum dots in low temperature photo-luminescence experiments. We find that the experimentally measured *Q*-factors are lower than theoretical values for small pillars. We also identify single photon emission from dots in square and rectangular pillars. In rectangular pillars we expect to see make polarized single photon sources.

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REFERENCES

[1] P. Michler, A. Imamoglu, M.D. Mason, P.J. Carson, G.F. Strouse, and S.K. Buratto, "Quantum correlation among photons from a single quantum dot at room temperature," *Nature* 406, 968 (2000).
[2] J.G. Rarity, "Quantum communications and beyond," *Phil. Trans. R. Soc. Lond.* A 361, 1507 (2003).
[3] P. Michler, A. Kiraz, C. Becher, W.V. Schoenfeld, P.M. Petroff, Lidong Zhang, E. Hu, A. Imamoglu, "A Quantum Dot Single-Photon Turnstile Device," *Science* 290, 2282 (2000).
[4] J.M. Gérard, D. Barrier, J.Y. Marzin, R. Kuszelewicz, L. Manin, E. Costard, V. Thierry-Mieg, and T. Rivera, "Quantum boxes as active probes for photonic microstructures: The pillar microcavity case," *Appl. Phys. Lett.* 66, 449 (1996).
[5] M. Pelton, J. Vučković, G.S. Solomon, A. Scherer, and Y. Yamamoto, "Three-dimensionally confined modes in micropost microcavities: quality factors and Purcell factors," *IEEE J. of Quantum Electronics* 38, 170 (2002).
[6] A.J. Bennett, *et al.,* "Polarization control of quantum dot single-photon sources via a dipole-dependent Purcell effect," *Phys. Rev. B* 72, 033318 (2005).
[7] Y.-L. D. Ho, T. Cao, P.S. Ivanov, M.J. Cryan, I.J. Craddock, C.J. Railton, and J.G. Rarity,“ Optimal design of single-photon sources emission from a quantum-dot in micro-pillar microcavity,” *Int. J. Quantum Information* 3, 229 (2005).
[8] R. Hanbury Brown and R.Q. Twiss, “Correlation between photons in two coherent beams of light”, *Nature* 177, 27-29 (1956).