Enhanced single-photon emission from single quantum dots in two-dimensional photonic crystal cavities

Xiulai Xu[1], Frederic S. F. Brossard[1], David A. Williams[1], Robert A. Taylor[2], Kwan H. Lee[2] and Felix Waldemann[2]
1 Hitachi Cambridge Laboratory, Hitachi Europe Ltd., Madingley Road, Cambridge CB3 0HE, United Kingdom
2 Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

We have designed and fabricated L3-type photonic crystals with high-density quantum dots embedded in the wafer. In these photonic crystals, a quality factor of ~3000 has been achieved,which greatly enhances the luminescence intensity of quantum dots when they are in resonance with cavity mode. An emission peak arising from a single quantum dot was used to perform second order correlation measurements employing a Hanbury-Brown and Twiss setup.Clear anti-bunching is seen, which indicates single photon emission.The emission lifetime is ~500 ps, which is less than that found in quantum dots without a photonic crystal (~1ns).

Background:

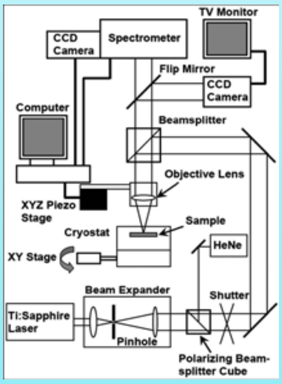
Efficient single-photon sources at high repetition rates are particularly desirable for quantum information processing. These can be produced by making use of the Purcell effect: for a dipole in resonance with (and placed at the anti-node of) a single mode of an optical cavity, with effective mode volume V and quality factor Q, the spontaneous emission rate of the quantum dots is enhanced by the Purcell factor:

$$F_p = \frac{3}{4\pi^2}\frac{Q\lambda^3}{Vn^3}$$

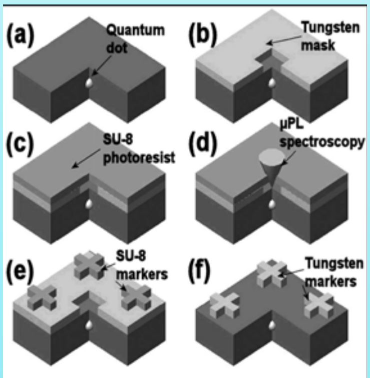
Nearly twenty years ago, Yablonovitch introduced the concept of full electromagnetic band-gap in 3D photonic crystals, with applications in inhibition of spontaneous emission. Photonic crystals are very useful when investigating the coupling between photons and cavities as they can be used to manipulate the emission from quantum dots. Coherent exciton-photon coupling provides the physical bases for real implementation quantum information processing. It is very desirable to have precisely controlled quantum dots and cavities matched both in energy and in spatial position.

Registration of single quantum dots:

We have registered the position of single InGaAs quantum dots using a cryogenic laser photolithography technique. The quantum dot positions were registered with an estimated accuracy of 50 nm by fabricating metal alignment markers around them. Photoluminescence spectra from quantum dots before and after marker fabrication were identical except for a small redshift 1 nm.



Schematic diagram of the apparatus used to perform micro-photoluminescence spectroscopy and laser photolithography.



Schematic diagram of the QD registration process. A QD sample a is coated with a tungsten mask b and then SU-8 photoresist is spin-coated on c. PL locates the QD d and an alignment marker is patterned in the SU-8 e. Subsequent RIE forms the final tungsten marker f.

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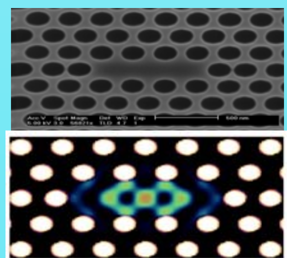
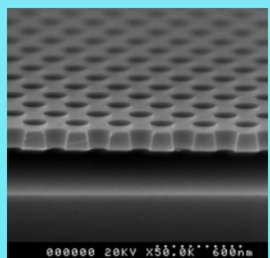
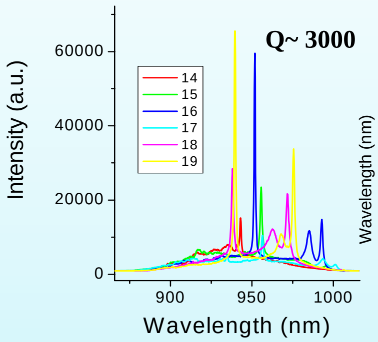
Photonic crystals:

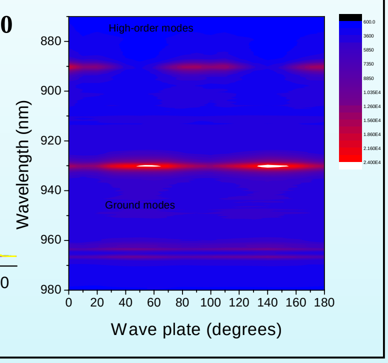
L3-type photonic crystal with high-density quantum dots embedded in the wafer. A scarified layer AlGaAs under GaAs photonic crystal slab has been removed with HF to form a so-called air-bridge, which enhances emission in the direction normal to the sample surface.



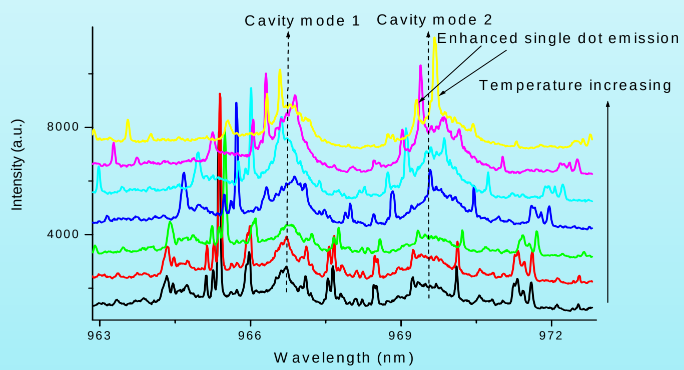


Cavity modes and linear polarization properties of photonic crystal with high dot density wafer:

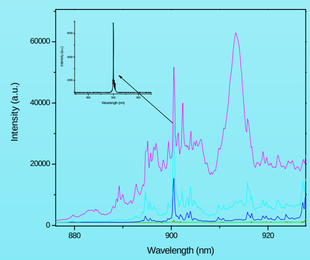




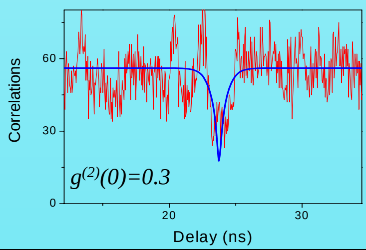
Temperature dependences



Enhanced PL emission of single quantum dot for single-photon sources:



PL spectra of a photonic-crystal device with difference excitation power at high energy regime. Inset: filtered PL spectrum.



Second-order correlation function of single-dot emission with Hanbury Brown and Twiss system

Summary and future work:

We have demonstrated the registration of a single quantum dot to within 50 nm, and the design and fabrication of L3-type photonic crystals with high-density quantum dots embedded in the wafer. Clear anti-bunching is seen from single quantum dot emission in the cavity, with the second order function at zero time delay being less than 0.5, indicating single photon emission. In the future, low dot density samples will be investigated with registered quantum dots in photonic crystal cavities.