Quantum Dots in 2D Photonic Crystals for Quantum Information Science

Andrey Bychkov[1,2], Michiel de Dood[2], and Dirk Bouwmeester[2,1], Stefan Strauf[3], Antonio Badolato[3], Kevin Hennessy[3], Pierre Petroff[3], and Evelyn Hu[3]

1- Centre for Quantum Computation, Clarendon Lab, Oxford University, OX1 3PU, UK
2 – Department of Physics, University of California at Santa Barbara, CA 93106, USA
3 – Department of Materials, University of California at Santa Barbara, CA 93106, USA

Single photons can be easily created in superpositions $\alpha\ |V> + \beta\ |H>$ of the vertical and horizontal polarization states. They can be further manipulated with linear optics elements, detected with increasing efficiency, and combined to form entangled states. This makes them the ideal candidates ('flying qubits') for quantum communication, quantum cryptography [1], and quantum computation [2].

However, the main missing point about photons at the moment is that information encoded in their quantum state cannot be stored for an arbitrary amount of time. For that reason, we propose to couple single photons coherently to the bright electron-hole transitions in individual semiconductor self-assembled quantum dots (QDs). Because of their discrete density of states QDs are sometimes named 'artificial atoms' and have shown optical dephasing times on the order of 0.5 ns [3] and optical spin lifetimes exceeding tens of nanoseconds [4]. These observations make quantum confined excitons very promising for storage and retrieval of quantum information. Moreover, recent demonstrations of generating single photons on demand [5], and excitonic Rabi oscillations [6] clearly indicate that individual QDs are reliable two-level quantum systems.

In order to preserve coherence of the quantum state during excitation, the photon has to be *resonant* in frequency with the QD transition. Non-resonant excitations lead to leakage of quantum information into the environment; e.g. by the generation of phonons in the surrounding material. In practice, resonant excitation is very challenging to implement, because the signal coming from the QD due to the exciton recombination is dwarfed by the scattered light at the same frequency. We have designed an experiment where two-photon interference effects [7] are used to distinguish the signal from the noise. It turns out, though, that the efficiency of photon absorption by the QD, together with the collection and detection of the re-emitted photons, must be improved significantly.

Here, we report on the preliminary optical study of samples with high density layers of InAs QDs embedded in a photonic crystal (PC) slab [8]. The slab consists of a 180 nm thick free-standing GaAs membrane with a square lattice of etched holes. A single-hole defect was created by removing a hole in the center of the array (see the inset of Figure 1). The in-plane periodic modulation of the refractive index n provides a 2D photonic bandgap, whereas the waveguiding effect restricts light from propagating in the vertical direction, thus forming a genuine three-dimensional confinement with extremely small mode volumes on the order of several $(\lambda/2n)^3$.

A high-resolution micro-photoluminescence setup was used to measure the emission of the sample. Figure 1 shows the observed emission spectrum from InAs QDs in the single-hole PC microcavity under non-resonant excitation at 798 nm by a 5-ps Ti:S mode-locked laser. The peak in the spectrum corresponds to photoluminescence from the QDs that are coupled to the cavity mode and a *Q*-factor as high as 1400 can be deduced from the data. Given the above mentioned mode volume, the expected Purcell factor of this cavity is of the order 200, giving rise to a large enhancement of the QD emission. Calculations for this structure predict Purcell-factors as high as 8000 [9], and holds promise for achieving the strong-coupling regime between the QD emitter and the cavity.

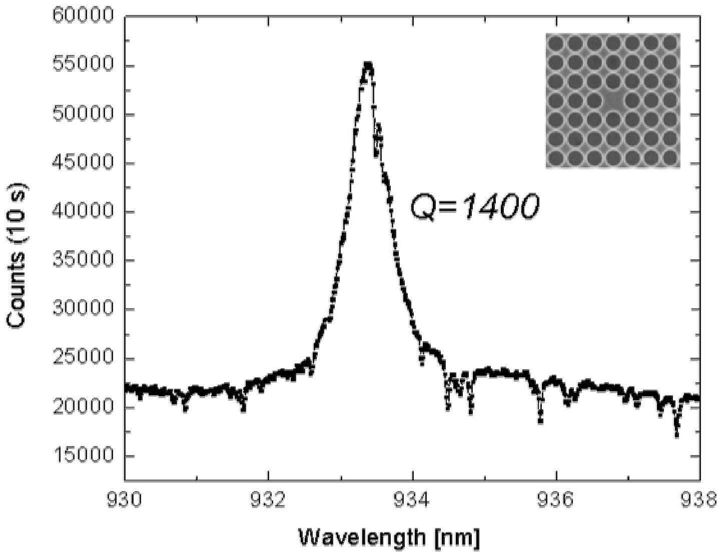

Figure 1: The photoluminescence spectrum at 4 K showing the cavity mode decorated by the QD emission peaks. The sample is pumped by a 5-ps Ti:S mode-locked laser at 580 μW. The inset shows a top-view scanning electron microscope image of the device. The size of the area is approximately 2 x 2 μm^2.

References:

1. D. Bouwmeester, A. Ekert, A. Zeilinger (Eds), *The Physics of Quantum Information* (Springer Verlag, Berlin, 2000).
2. E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46 (2001).
3. P. Borri *et al.*, Phys. Rev. Lett. **87**, 157401 (2001).
4. M. Paillard *et al*., Phys. Rev. Lett. **86**, 1634 (2001).
5. P. Michler *et al.*, Science **290**, 2282 (2000); C. Santori *et al.*, Phys. Rev. Lett. **86**, 1502 (2001); Z. Yuan *et al.*, Science **295**, 102 (2002).
6. T. Stievater *et al.*, Phys. Rev. Lett. **87**, 133603 (2001); H. Kamada *et al.*, Phys. Rev. Lett. **87**, 246401 (2001).
7. C. K. Hong, Z. Y. Ou, L. Mandel, Phys. Rev. Lett. **59**, 2044 (1987).
8. C. Reese *et al.*, Appl. Phys. Lett. **78**, 2279 (2001); C. Reese, B. Gayral, B. D. Gerardot, A. Imamoglu, P. M. Petroff, and E. Hu, J. Vac. Sci. Technol. B **19**, 2749 (2001).
9. H.-Y. Ryu, J.-K. Hwang, and Y.-H. Lee, J. Quantum Electron. **39**, 314 (2003).