# Quantum-State Transfer Between Photons and Nanostructures

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## Introduction

Photons have proven to be most useful for encoding special quantum states and for transmitting them through free space or optical fibers. For local quantum-state operations photons are less favorable and localized quantum systems are desirable. In this respect exciton or single-electron spin states in quantum dots are particularly attractive. The main aim of this research program is to coupling single photons to single quantum dots and to establish the transfer of quantum states between light and solid-state nano structures. In the first 18 months of the project we made significant progress in three aspects of the problem; I) introducing micro-cavities around the quantum dots to enhance the quantum-dot interaction with photons, II) creating multi-photon entangled states that are optimized for quantum state transfer, III) coupling exciton states of neighboring quantum dots through virtual photon interaction.

## I. Quantum Dots in Micro Cavities

We have fabricated various semiconductor photonic crystals and micro-pillars with active layers of single quantum dots. The best photonic crystal cavities produced at UCSB (collaboration with the group of Prof. E. Hu) so far are L3-type (three missing air holes) with embedded self-assembled InAs/GaAs quantum dots as active material. In order to achieve spectral overlap of the photonic crystals with the embedded quantum dot gain medium, the target wavelength of a photonic crystal cavity mode can be tuned prior to fabrication by a proper design of the lattice constant, hole radius and e-beam dose. Devices have been fabricated with varying single-mode emission wavelength between 910-975 nm. Fig.1 shows a micro-PL spectrum for a device emitting at 960.3 nm. In this case, the mode emission spectrally overlaps with the ground-state transition wavelength of the QD ensemble centered at 965 nm with a FWHM of 40 nm. The inset in Fig.1 shows a scanning electron micrograph (SEM) around the L3-type defect region. The devices have been optimized for high quality factors, small mode volumes and a large effective refractive index by varying the size and

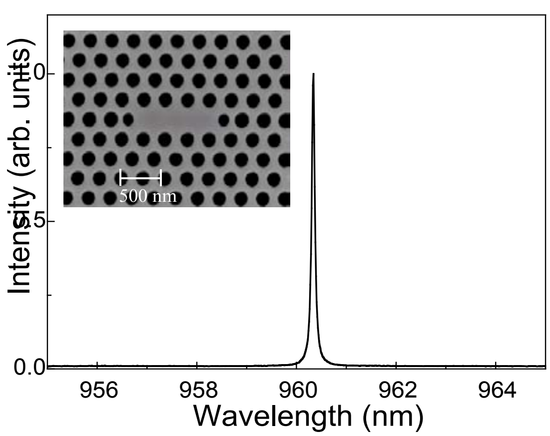


Fig. 1. Micro photoluminescence spectrum of the cavity mode under 780 nm cw excitation at a pump power of 3 _W at 4.5 K. Inset: SEM of an L3-type photonic crystal microcavity with 260 nm lattice constant around the defect.

position of the two holes adjacent to the line defect. As a result, single-mode lasing has been found for devices emitting between 910-975 nm showing ultra-low lasing thresholds down to 160 nanoWatt (see Fig. 2). Measured quality factors at the lasing threshold are as high as Q = 9800, while calculated mode volumes are as small as 0.7 cubed wavelengths. In addition, the field distribution is localized inside the material rather than inside the air-holes as it is the case for the single defect square-lattice geometry (S1). These properties make such cavities very attractive for single QD cavity-Quantum Electro Dynamics (QED) experiments.

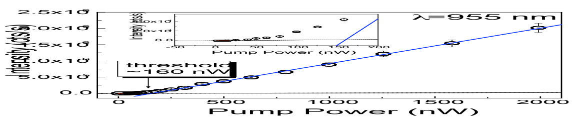


Fig. 2. Pump power dependence of a laser cavity emission at 955 nm. The solid lines are linear fits to the data at low (black) and high (blue) pump powers. Their intersection corresponds to a lasing threshold of 160 nW. Inset: Magnification of data in the low pump power regime. Data are taken at 4.5 K.

The higher the quality of the cavity the more accurate the cavity tuning has to be in order to be resonant with individual quantum dots. We observed a significant cavity mode drift (Fig. 3), which turned out to be related to a thin film deposition on the cold sample. Heating the sample removed the thin film. Currently we are exploring ways of permanently tuning photonic crystal by controlled thin film depositing. In addition positioning of QDs inside photonic crystals is being developed [1].

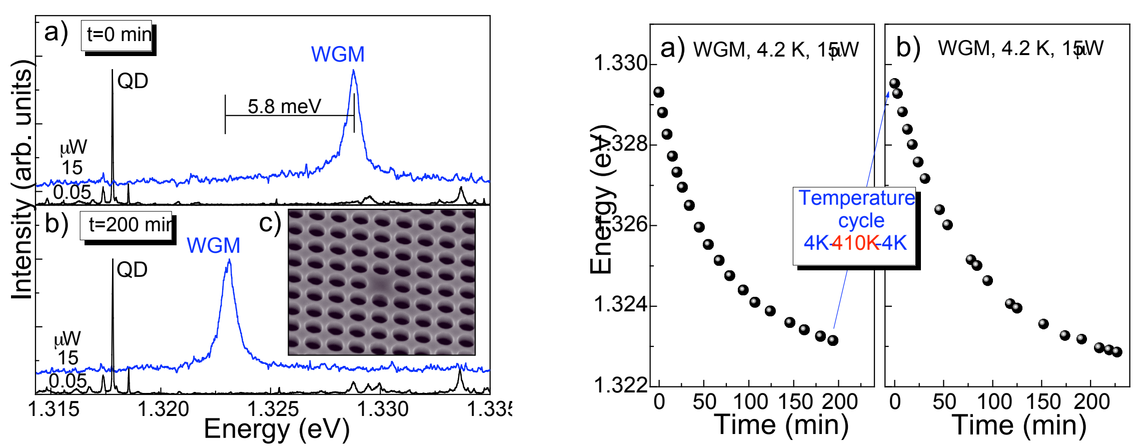


Fig 3. Left panel: slow S1 cavity mode drift of up to 6meV as a result of thin film deposition. Right panel: by increasing the temperature from 4K to 410K the film is removed and the cavity frequency is reset.

In addition, we study single QD in micro pillars with oxidation apertures to confine the optical mode in a small volume away from the rough pillar sidewalls. Micropillars have the advantage that the optical mode is directional and therefore allows fro an efficient coupling to an external optical mode. We obtained record-high micro pillar Q factors of 55.000.

## II. Multi-Photon Entangled States

We have focused on creating novel quantum states of light that are specially suited for the transfer of quantum states from light to matter. In particular, we created entangled light states that have two output modes that each contain up to 50 photons [2]. The entanglement between the two modes is such that even in the case that only one photon in each mode is detector or transferred entanglement persists. Therefore such states are very interesting for establishing entanglement between excitations in quantum dots and photons. We also investigated the use of nonlinear photonic crystals to create entangled photons [3].

## III. Coupling Quantum Dots

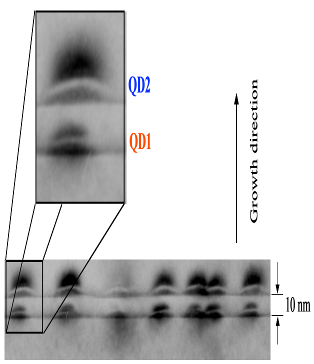


Fig 4. Strain-induced pairs of coupled QDs

We studied vertically stacked coupled quantum dots (Fig. 4). The InGaAs dots are grown on a GaAs substrate and are separated by 45nm to 120nm for different samples. The photon emission from individual quantum dot pairs has been studied by analyzing the time intervals between subsequent photon emissions at different emission frequencies. This confirms that the QDs indeed form a single quantum system, extending the artificial atom analogy to the level of artificial molecules [4].

**References**

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