The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR 1760 - 11

COLLEGE ON

PHYSICS OF NANO-DEVICES

10 - 21 July 2006

Coupling of Single Quantum Dots to Single Nanocavity Modes

Presented by:

Atac Imamoglu

ETH-Zürich, Switzerland

Coupling of Single Quantum Dots to Single Nanocavity Modes

A. Imamoglu
Quantum Photonics Group, Department of Physics
ETH-Zürich

Outline

1) Brief overview of cavity quantum electrodynamics (QED)
2) Single quantum dot (QD) as a two-level emitter
3) Nano-cavities based on photonic crystal defects
4) Cavity-QED using a single QD embedded in a nano-cavity
5) Outlook

Cavity Quantum Electrodynamics (cavity-QED)

- Single two-level (anharmonic) emitter coupled to a single cavity mode is described by the Jaynes-Cummings (JC) Hamiltonian

$$H_{JC} = \hbar\omega_{eg}\sigma_{ee} + \hbar\omega_c a_c^+ a_c + \hbar g_c(\sigma_{eg} a_c + a_c^+ \sigma_{ge})$$

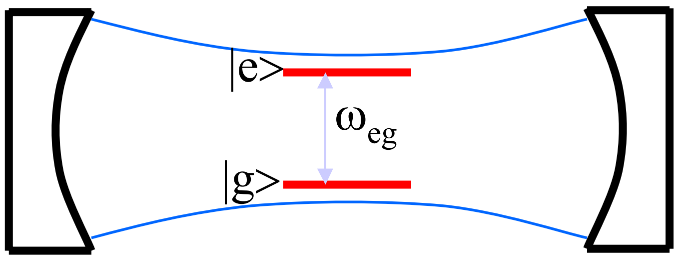
An exactly solvable model

- ω_{eg} : emitter frequency
- ω_c : cavity frequency
- g_c : cavity-emitter coupling strength

In all optical realizations:

$$g_c \ll \omega_c \approx \omega_{eg}$$

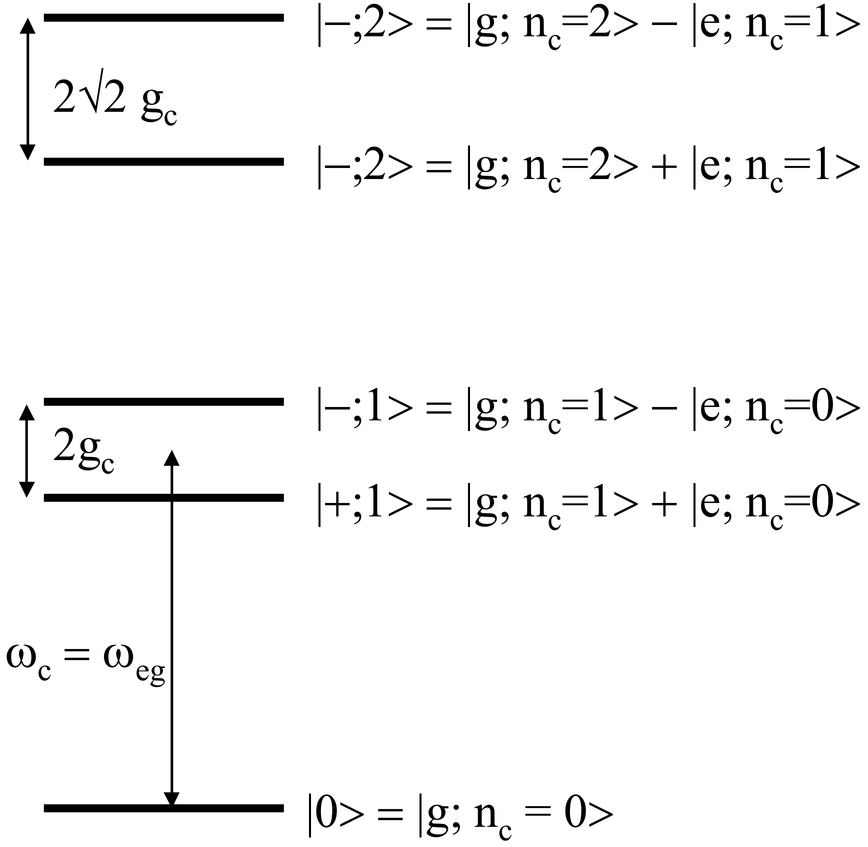
$$10^{8} \qquad 10^{15} \quad 10^{15}$$



For electric-dipole coupling:

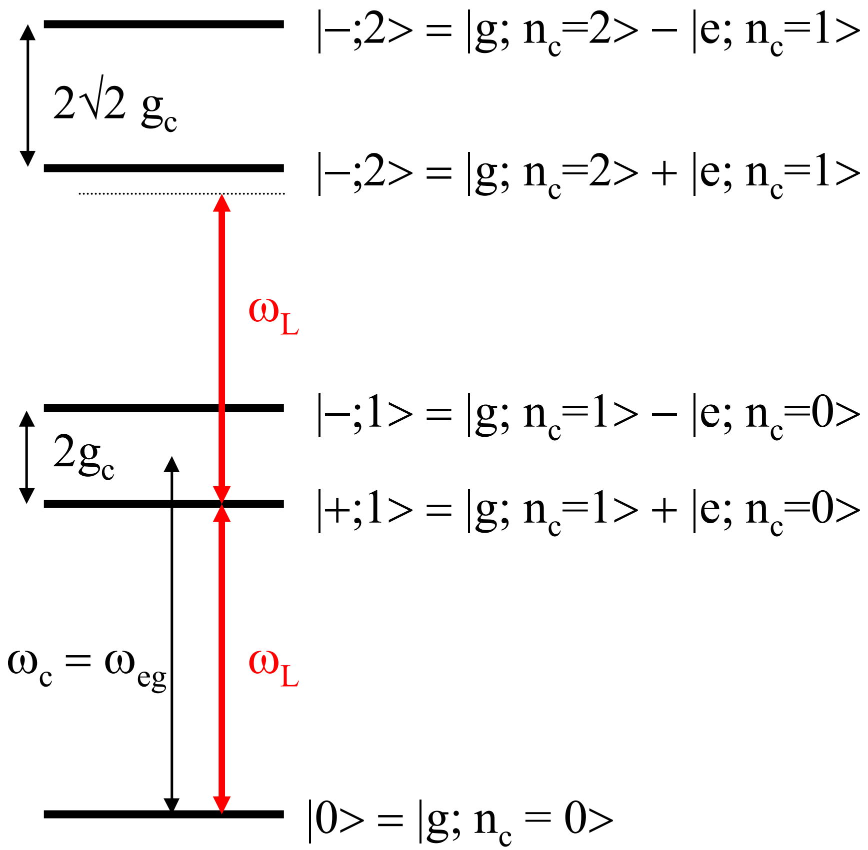
$$g_c = \left(\frac{\hbar\,\omega}{2\varepsilon_0 \epsilon V}\right)^{1/2} q \langle e|\, \varepsilon.\mathbf{r}\, |g\rangle$$

Eigenstates of the JC Hamiltonian



- The eigenstates of the coupled system are entangled emitter-cavity states
- The spectrum is anharmonic: the nonlinearity of the two-level emitter ensures that the coupled system is also anharmonic.

Eigenstates of the JC Hamiltonian



- The eigenstates of the coupled system are entangled emitter-cavity states
- The spectrum is anharmonic: the nonlinearity of the two-level emitter ensures that the coupled system is also anharmonic.

Ex: A laser (ω_L) that is resonant with the |0>-|+;1> transition will be off-resonant with all other transitions; the emitter-cavity molecule may act as a two-level system.

$\Rightarrow$ Single photon blockade!

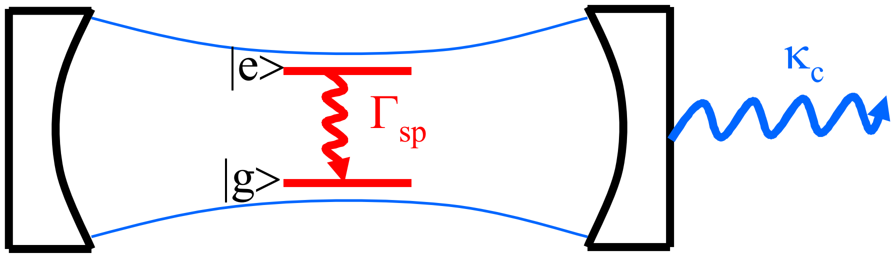
Dissipative cavity-emitter coupling: an open quantum system

- Single two-level (anharmonic) emitter coupled to a single cavity mode is described by the non-Hermitian JC Hamiltonian

$$\tilde{H}_{JC} = \hbar\omega_{eg}\sigma_{ee} + \hbar\omega_c a_c^+ a_c + \hbar g_c(\sigma_{eg}a_c + a_c^+\sigma_{ge}) - i\frac{\hbar}{2}\Gamma_{sp}\sigma_{ee} - i\frac{\hbar}{2}\kappa_c a_c^+ a_c$$

+ noise terms describing quantum jumps associated with spontaneous emission and cavity decay processes.

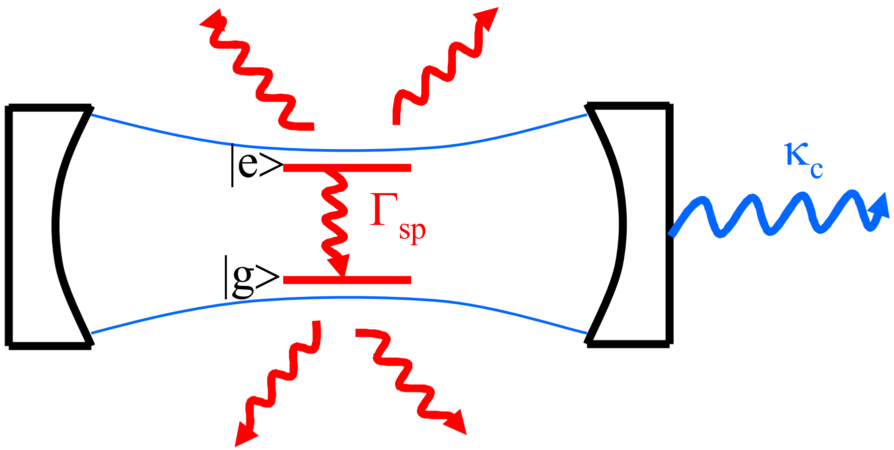
$\boxed{\equiv \text{ description using a markovian master equation}}$



Purcell regime: $g_c^2 >> \kappa_c \Gamma_{sp}$

Strong coupling: $g_c > \frac{\Gamma_{sp}}{4}, \frac{\kappa_c}{4}$

A simple application of cavity-QED: Purcell effect



There are two channels for radiative decay in the presence of a cavity:

i) Spontaneous emission rate due to vacuum modes surrounding the emitter remain mostly unchanged: Γ_{sp}

ii) The interaction with the cavity mode leads to an irreversible decay of emitter excitation; using Fermi's golden rule (valid when $\kappa_c > g_c$) gives

$$\Gamma_{Purcell} = \frac{g_c^2}{\kappa_c} \qquad \Rightarrow \text{Purcell effect: } \Gamma_{\mathrm{Purcell}} > \Gamma_{\mathrm{sp}}$$

$\Rightarrow$ Purcell regime enables many elementary tasks in quantum information processing, such as intra-conversion of spin and polarization qubits and generation of spin entanglement.

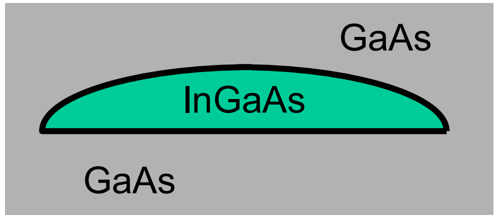
Signatures of the strong coupling regime

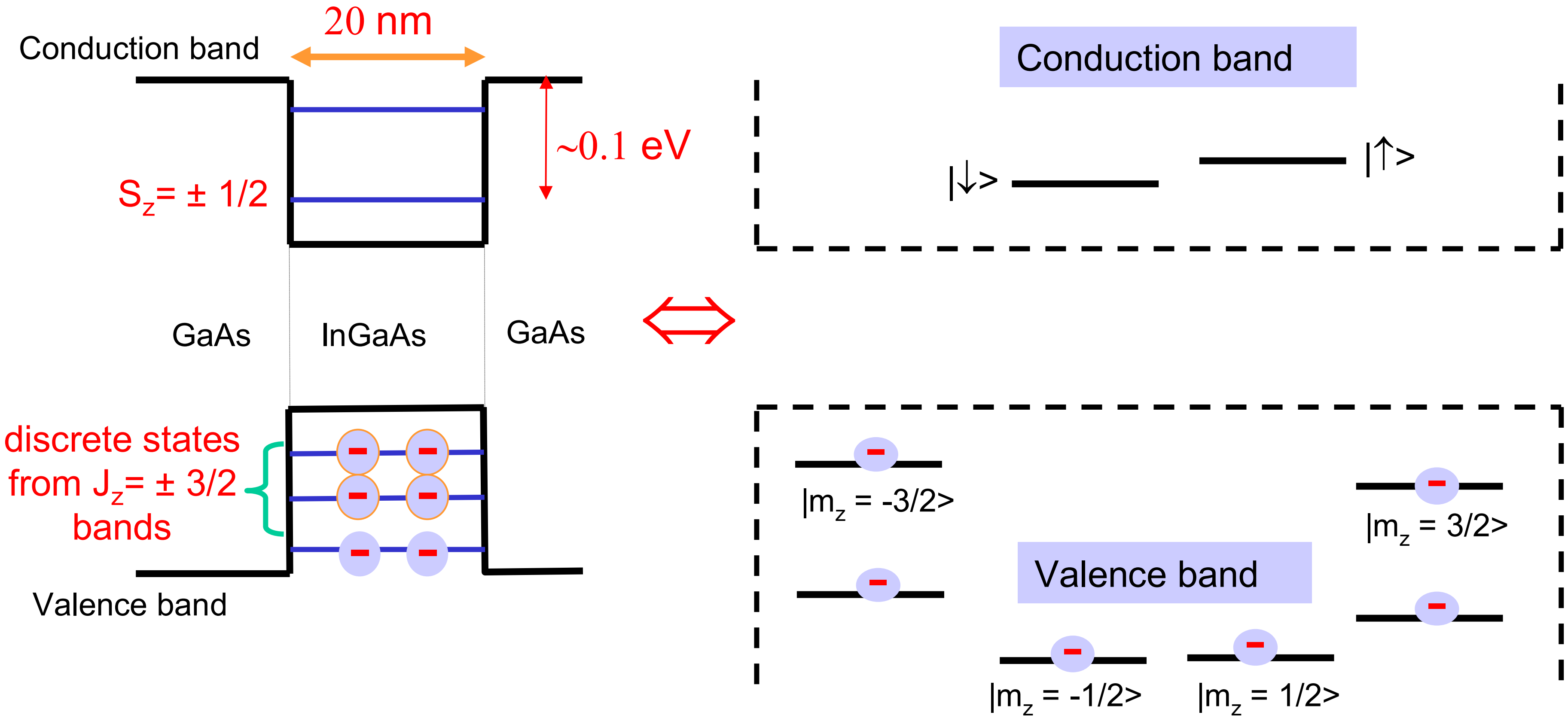
- Frequency domain: anti-crossing of the cavity and emitter like resonances as the cavity (emitter) is tuned on to resonance with the emitter (cavity).

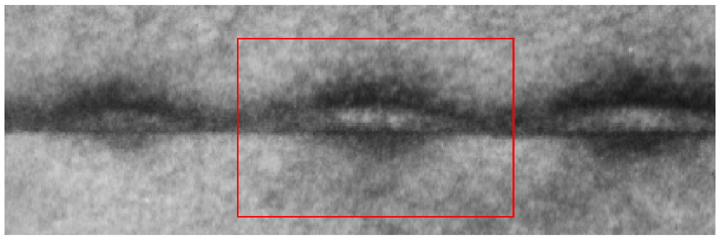
- Time-domain: vacuum Rabi oscillations in the time-dependence of the spontaneous emission intensity, upon initial excitation of state |e>.

- Photon blockade: proves that strong coupling is achieved using a single anharmonic emitter coupled to the cavity.

Quantum dots (QD) with strong confinement along the growth direction







Cross-sectional TEM

- QDs have discrete states for electrons & holes.
- QD location is fixed by growth.
- Each QD has a different transition energy.

Quantum dots as two-level emitters in cavity-QED

- Quantum dots do not have random thermal motion and they can easily be integrated in nano-scale cavities.
- Just like atoms, quantum dots have spontaneous emission broadened emission lines.
- Exciton transition oscillator (dipole) strength ranges from 10 to 100 (depending on the QD type) due to a collective enhancement effect.

- QDs nucleate in random locations during molecular beam epitaxy growth;
- The size and hence the emission energy of each QD is different; the standard deviation in emission energy is ~50 meV.

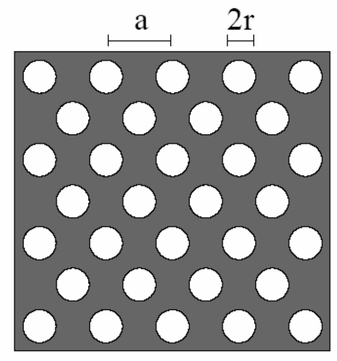
$\Rightarrow$ Obtaining spatial and spectral overlap between the QD and the cavity electric field is a major challenge.

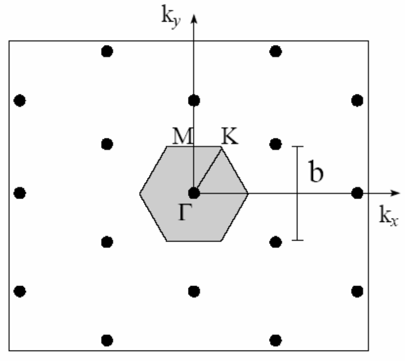
Light confinement in photonic crystals

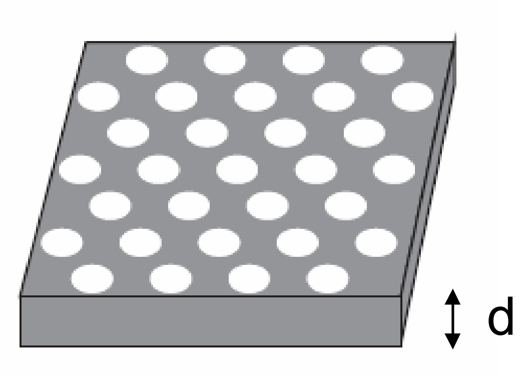
- A photonic crystal (PC) has a periodic modulation in dielectric constant and modifies the dispersion relation of electromagnetic fields to yield allowed energy bands for light propagation. For certain crystal structures there are band-gaps: light with frequency falling within these band-gaps cannot propagate in PCs.
- A defect that disrupts the periodicity in a PC confines light fields (at certain frequencies) around that defect, allowing for optical confinement on length scales ~ wavelength.
- A two dimensional (2D) PC membrane/slab defect can confine light in all three dimensions: the confinement in the third dimension is achieved thanks to total internal reflection between the high index membrane and the surrounding low-index (air) region.

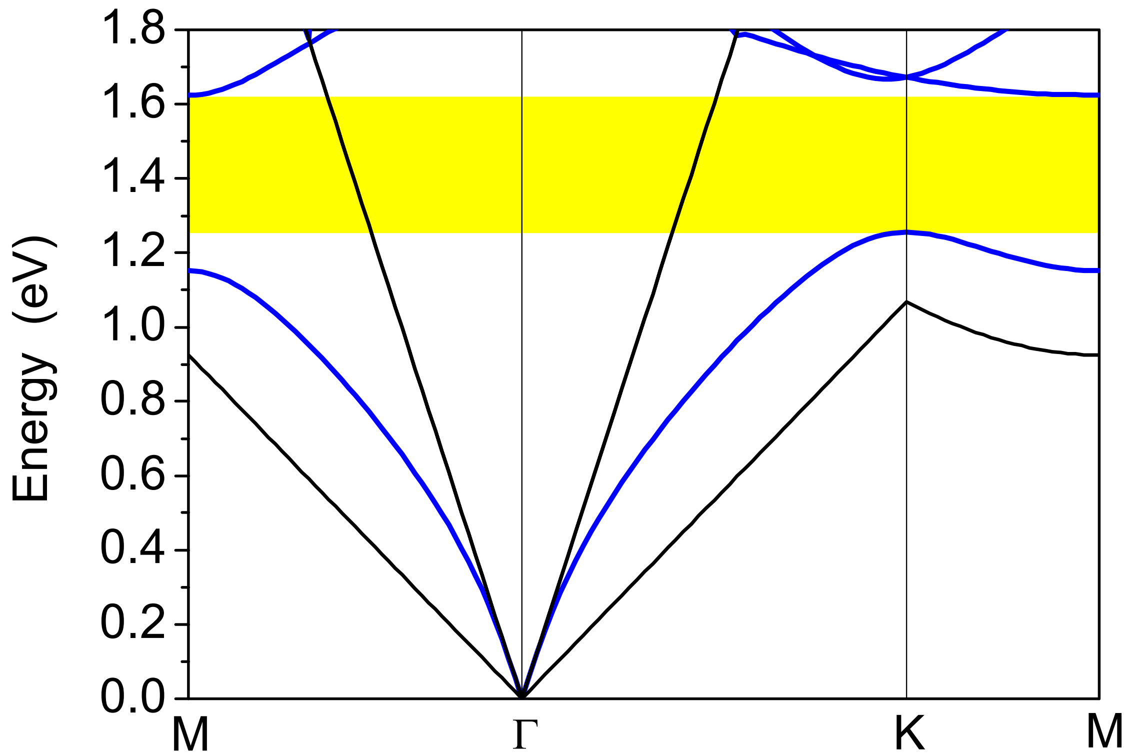
Note: Total internal reflection and mirrors based on periodic modulation of index-of-refraction are key ingredients in all solid-state nano-cavities.

Photonic Crystal Slabs









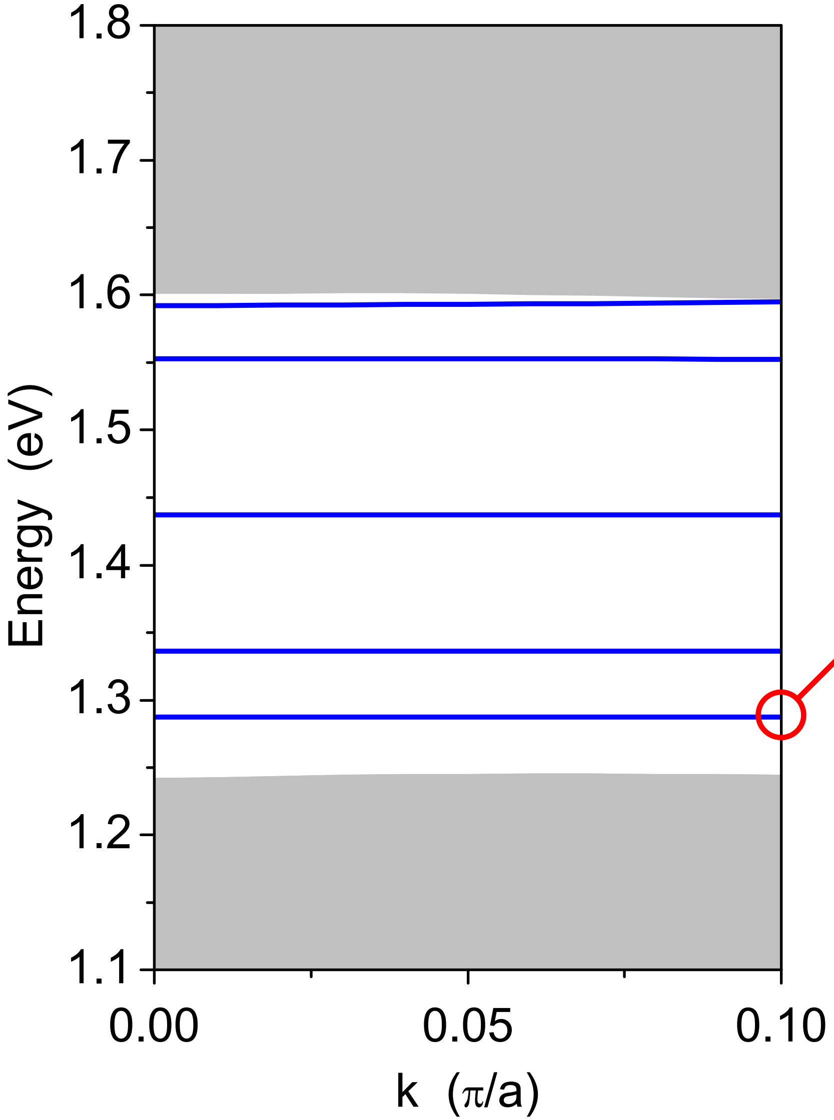
Our slabs:

126 nm-thick GaAs

a=260 nm, r/a=0.29

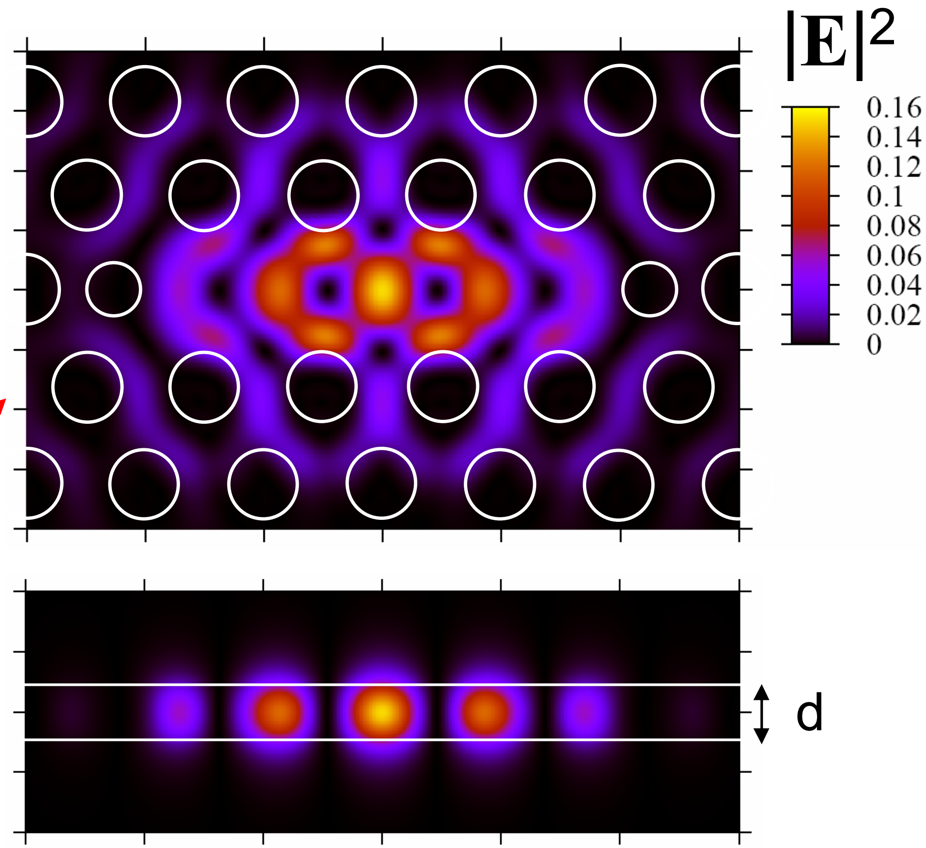
Photonic band gap
~ 990nm -760nm

Optimized High-Q, small V_{eff} cavities



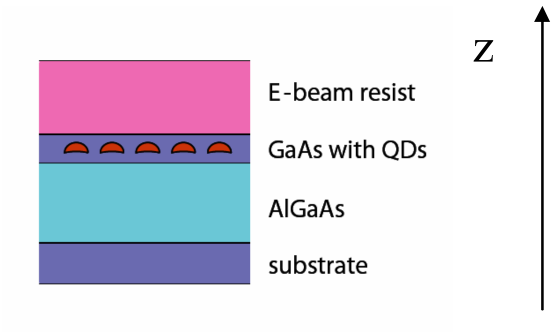
Fundamental cavity mode:

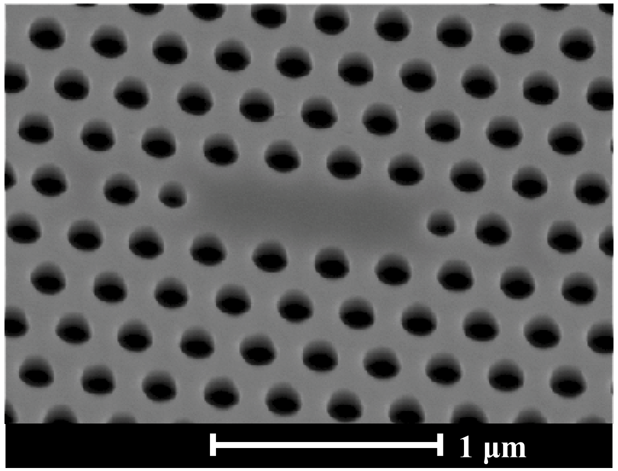
λ_{cav}=960 nm, $Q \approx 3\times10^5$, $V_{eff} \approx 0.7\ (\lambda/n)^3$



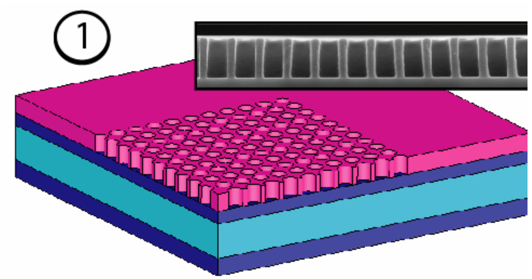
Vertical confinement by TIR, planar confinement by PBG!

Photonic crystal fabrication

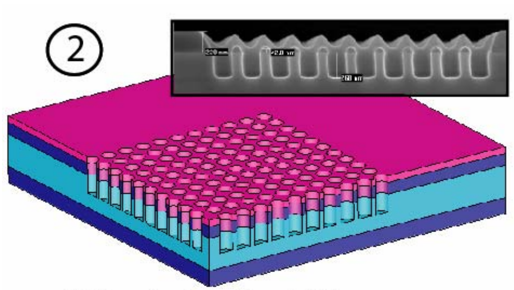




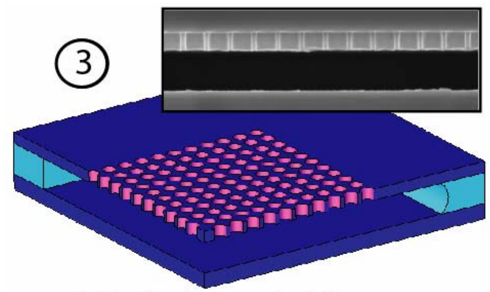
$Q \approx 2\times10^4$, $V_{eff} \approx 0.7\ (\lambda/n)^3$



Electron-beam lithography



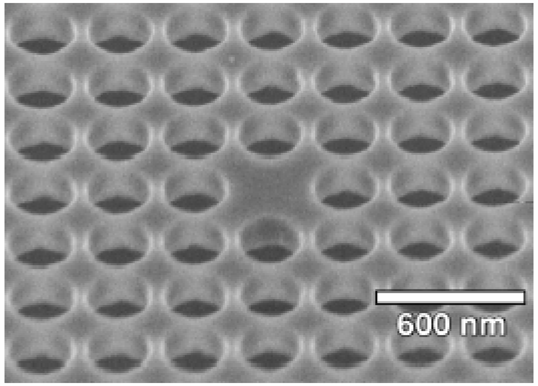
ICP anisotropic etching



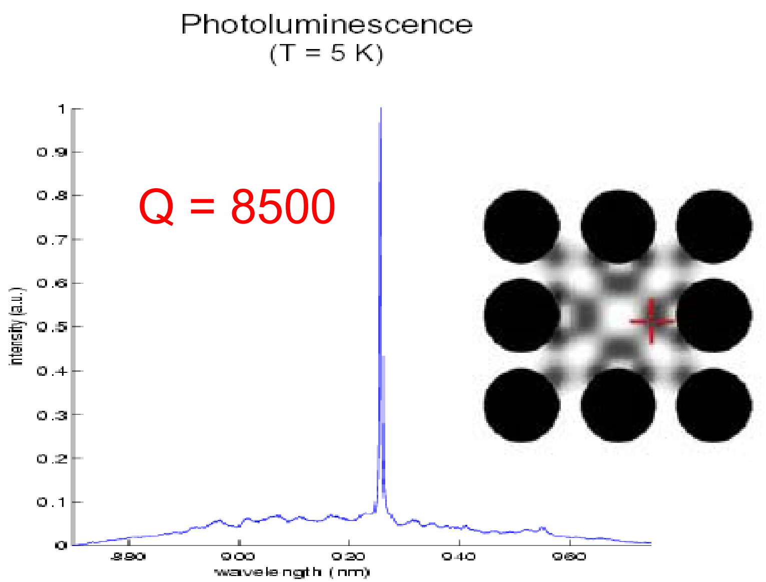
HF selective wet etch

Single nano-cavity in a 2D GaAs photonic crystal membrane

S1 defect cavity
(t = 180 nm, a = 300 nm, r = 111 nm)



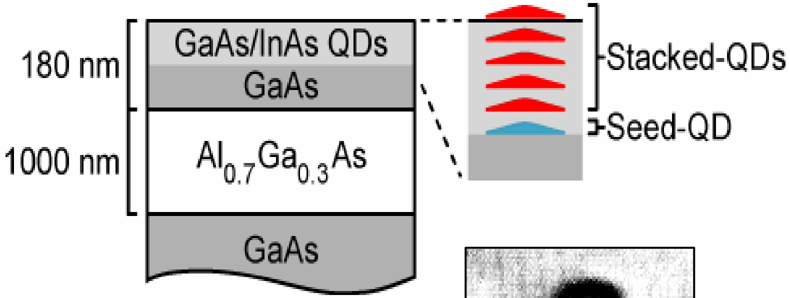
180 nm thick GaAs membrane (with a high density of embedded QDs) obtained by etching away the Al containing layer underneath.

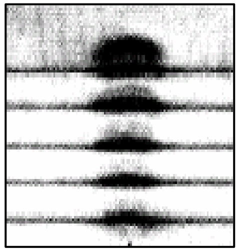


- Recent results (Noda *et al.*) demonstrated Q > 1,000,000 for $V_{cav} = (\lambda/n)^3 \sim 0.1\ \mu m^3$. Predicted $g_c^2 > 10{,}000\ \Gamma_{sp}\ \kappa_c$ (had that cavity contained a single QD)!

- Two major obstacles for doing QD cavity-QED:
  a) Spatial overlap of a single QD and the cavity mode
  b) Spectral overlap of QD and cavity resonances

Active positioning a single QD at the anti-node of a defect cavity
(A. Badolato & K. Hennessy)

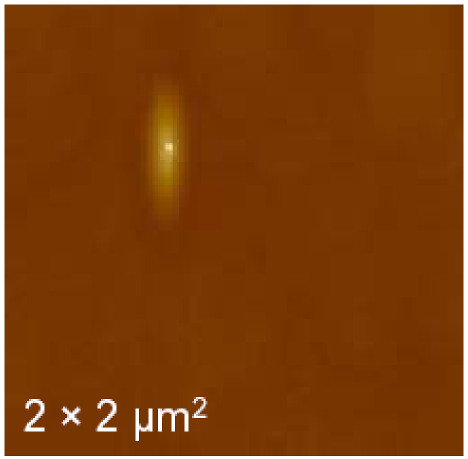




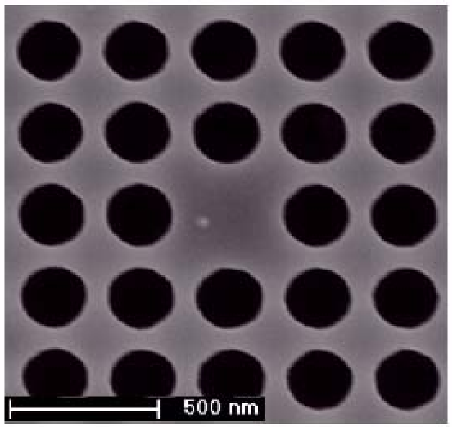
1) Identify QD location with 25 nm resolution using AFM or SEM

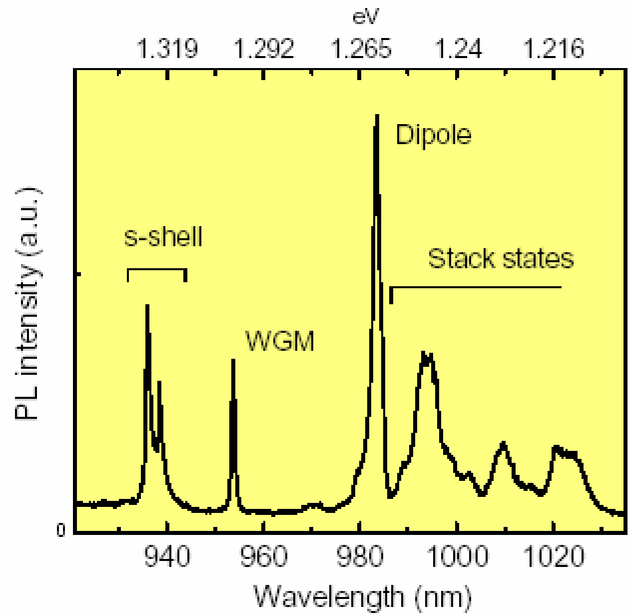
2) Determine QD exciton energy

3) Fabricate PC defect to ensure spatial and near spectral overlap

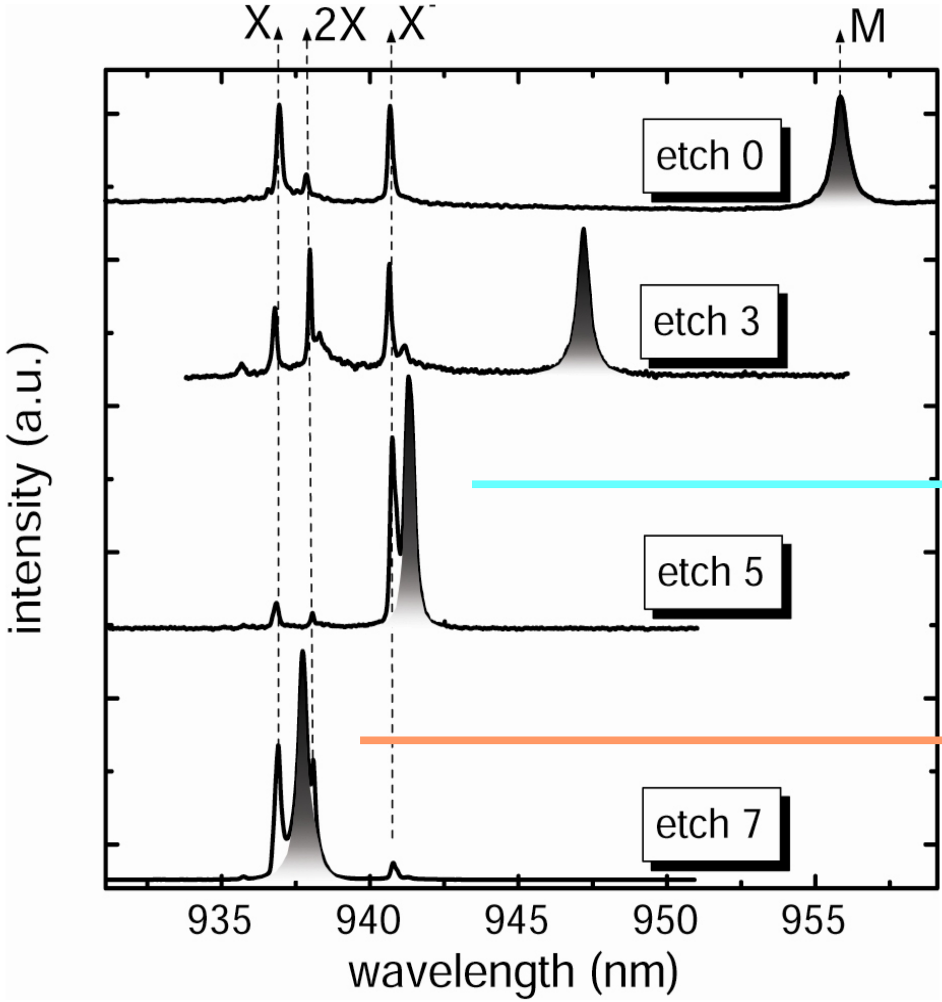


AFM topography of a single stack





Tuning a cavity-mode into near-resonance with a QD line by digital etching

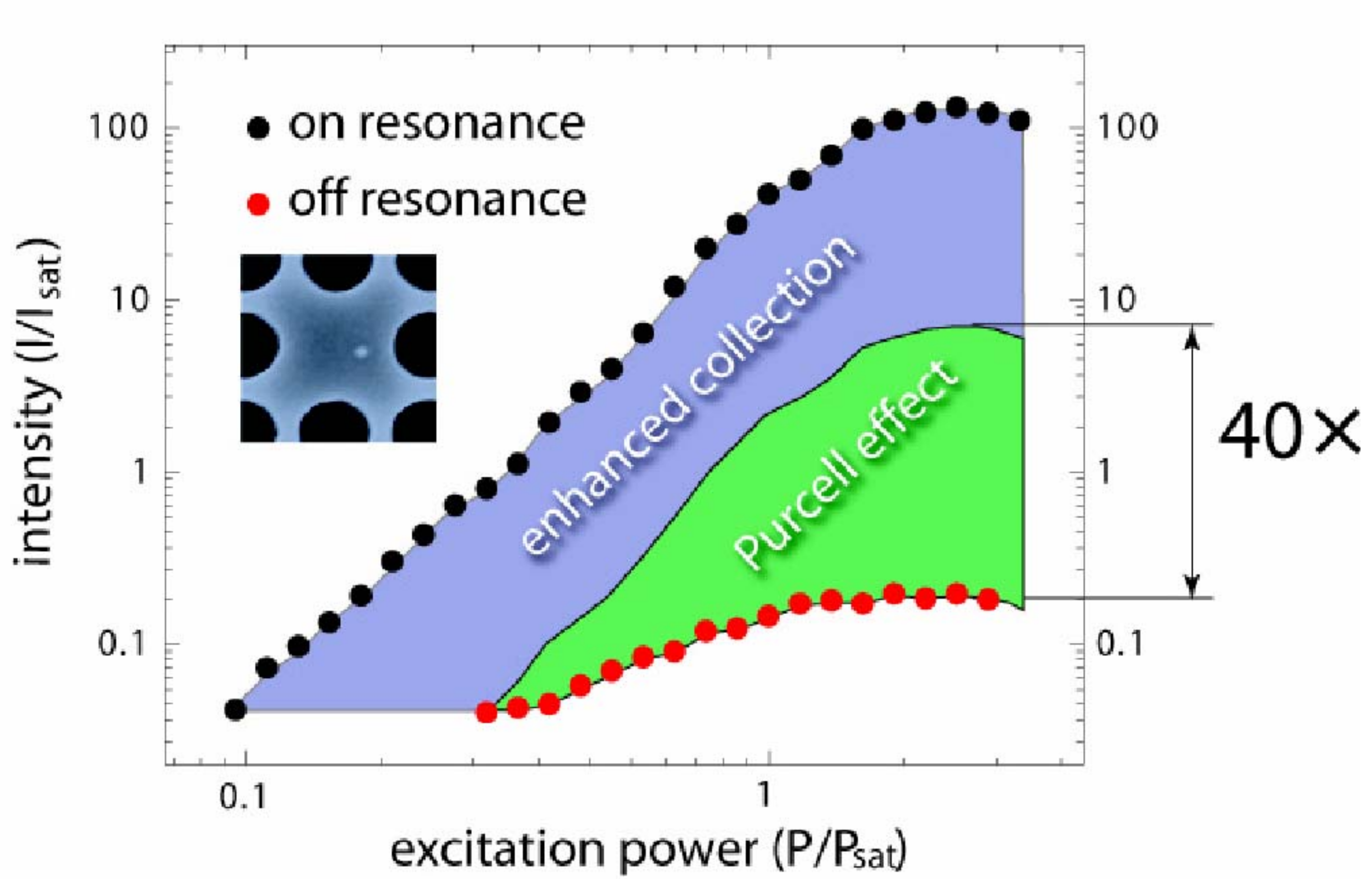


Each etching cycle consists of allowing a thin oxide layer to form and then removing it by selective wet etching

Temperature tuning: cavity-charged-exciton (trion) resonance

Temperature tuning: cavity-exciton resonance
Magnetic field tuning: cavity-biexciton resonance

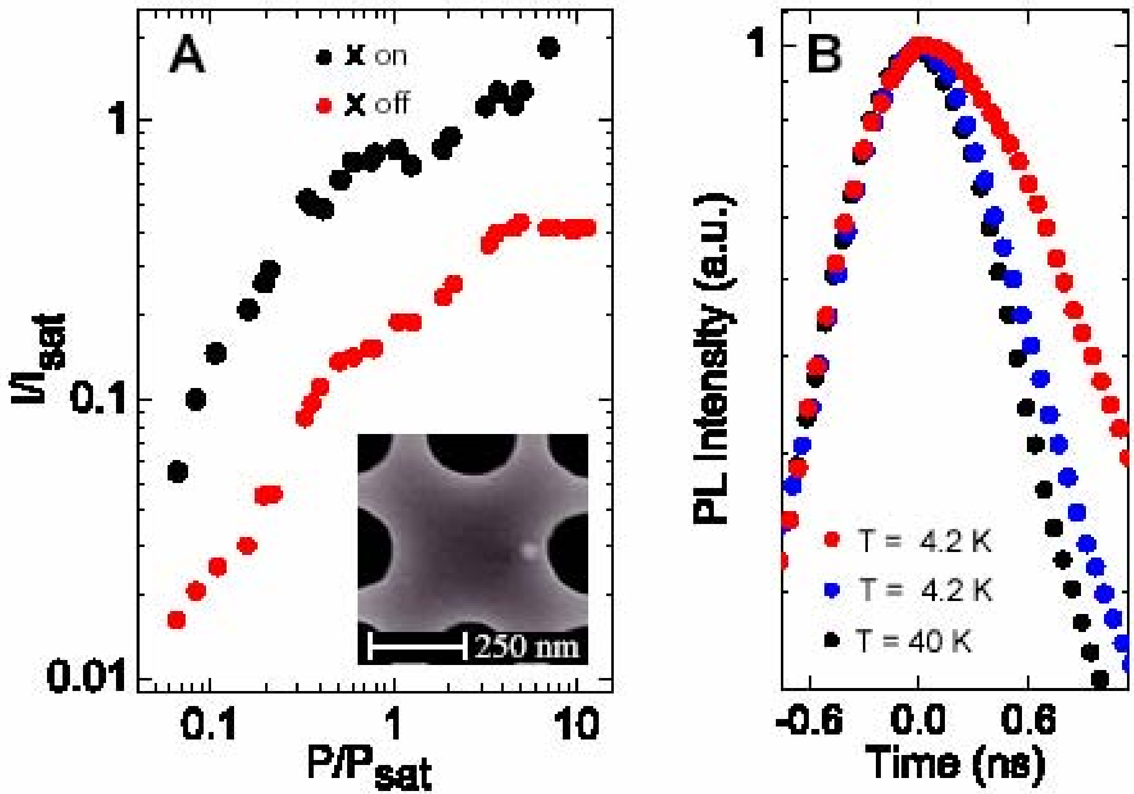
Cavity-QD resonance by temperature tuning

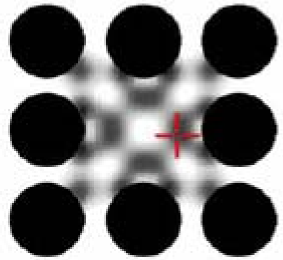


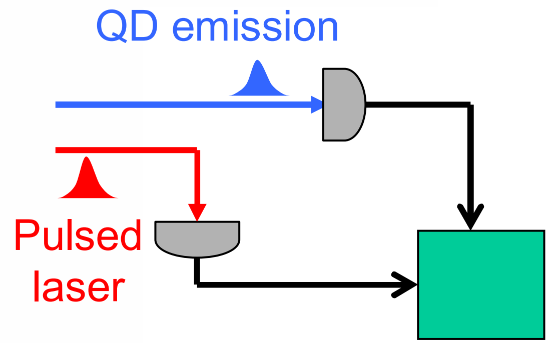
⇒ Resonant enhancement of X- luminescence intensity by a factor of 700: cavity-QD coupling g_c ~ 80 μeV and Purcell factor F_P ~ 40.

Direct measurement of the Purcell effect

QD-cavity structure with the least successful
spatial QD-cavity spatial overlap



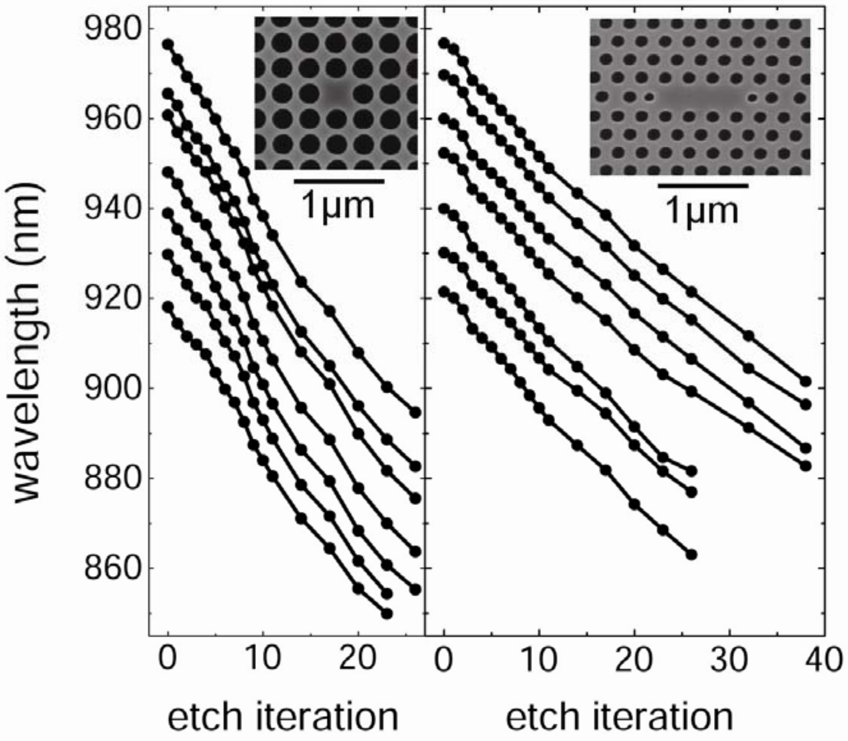


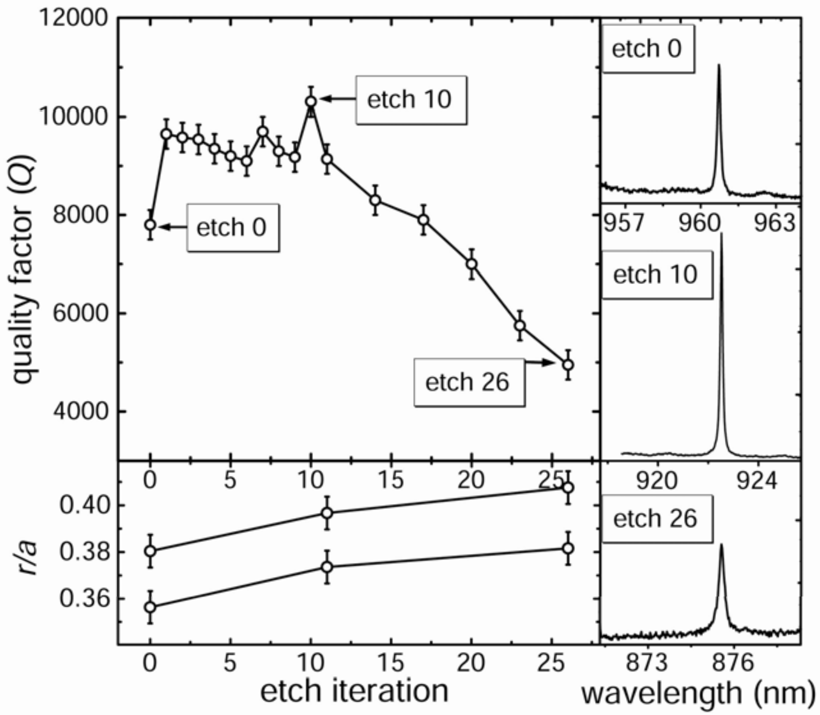


Time-correlated single-photon counting shows reduction of QD lifetime from 1.0 ns to 0.2 ns on resonance.

Deterministic cavity-QED: we were able to observe resonance enhancement of luminescence in all 4 structures we studied.

How well does digital etching work?



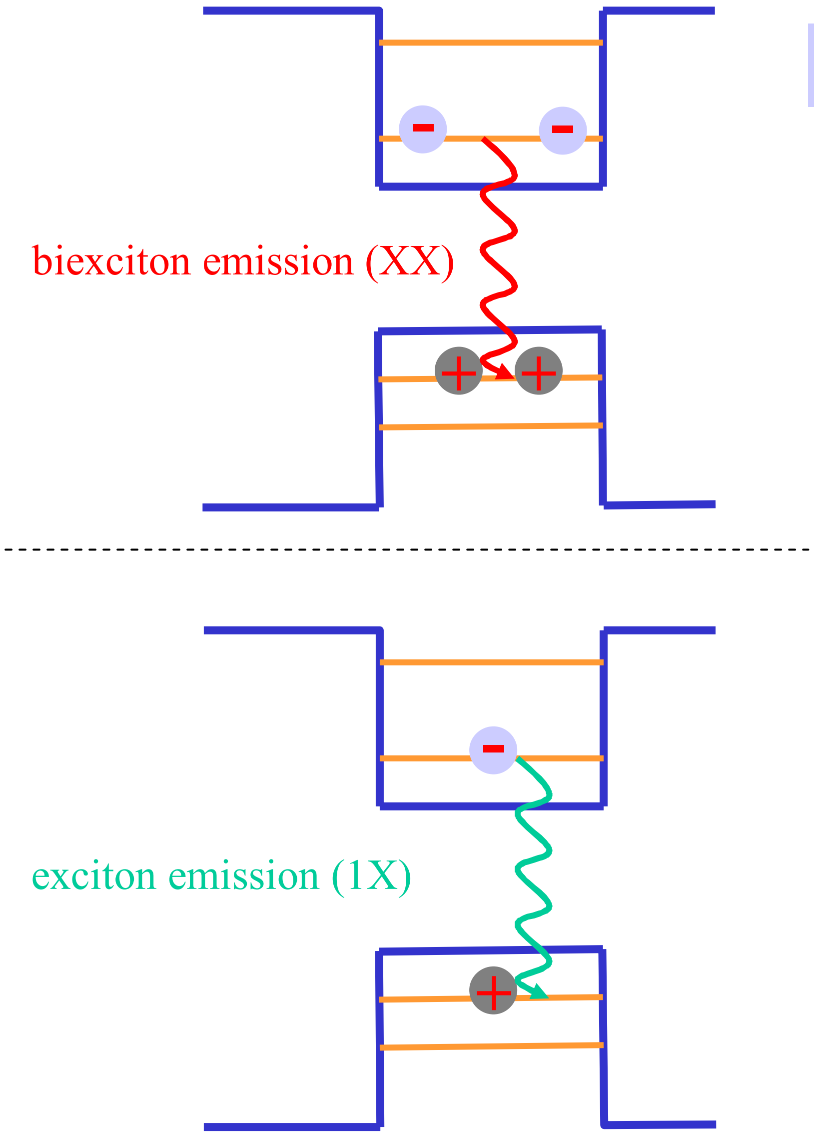


The magnitude of cavity blue-shift at each etching step depends on the cavity:

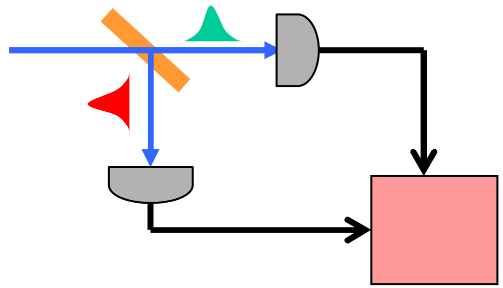
S1 $\Rightarrow$ 3 nm/step

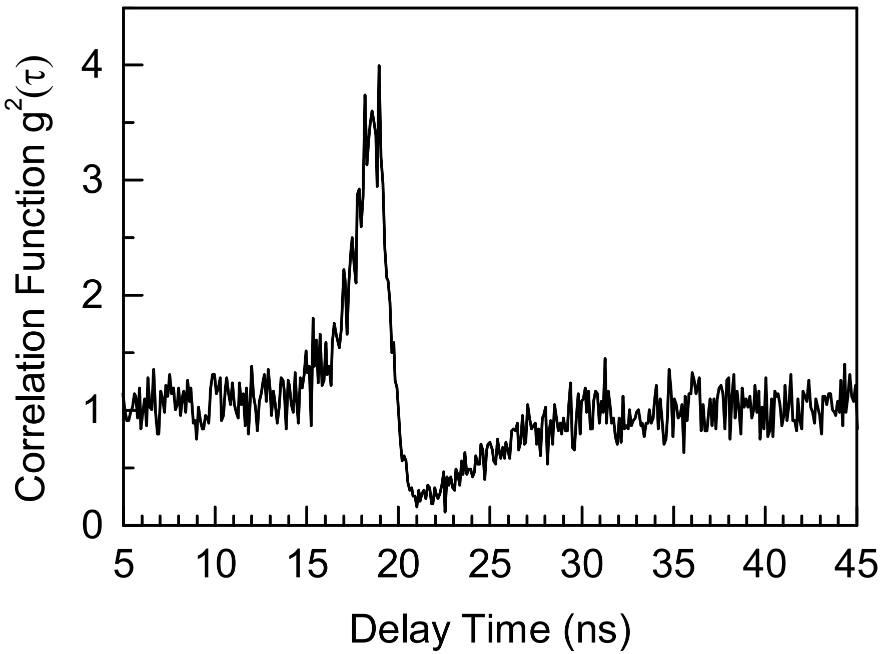
L3 $\Rightarrow$ 2 nm/step

Higher-order optical excitations in a quantum dot

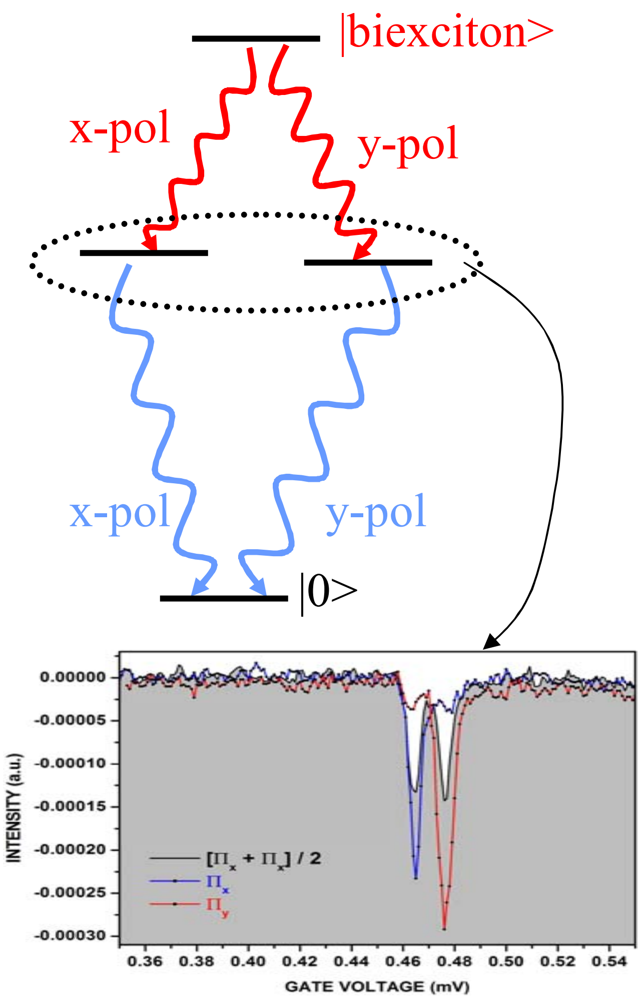


Photon cross-correlation measurement





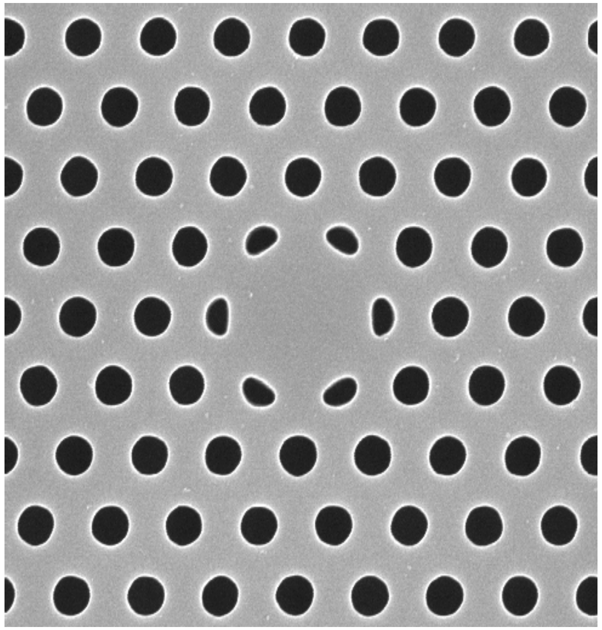
Polarization entangled photons from QDs



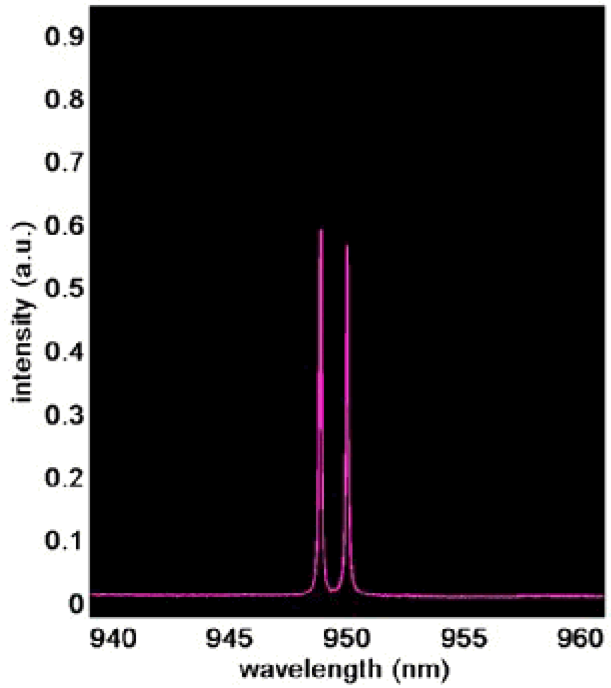
- In the absence of anisotropic exchange splitting (ΔE_{exch}) of the exciton line, cascaded emission from a QD biexciton generates polarization entangled photons at ω_{XX} and ω_X.
- When $\Delta E_{exch} > \Gamma_{spon}$, the polarization can be identified by measuring energy; the output state has classical polarization correlations.
- By coupling the QD to a nano-cavity, we can ensure that the Purcell enhanced decay rate of the excitonic states well exceed ΔE_{exch}; the output state will be entangled if the Purcell factor is > 20.

The nano-cavity must support two (nearly) degenerate modes with orthogonal polarization (Milburn et al.)

Photonic crystal nano-cavity supporting degenerate modes with orthogonal polarizations



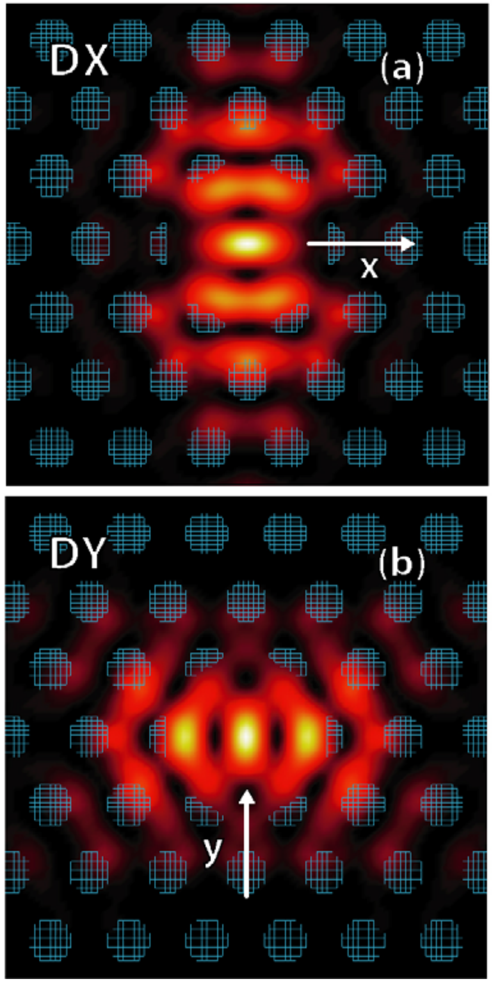
SEM image of a calzone cavity

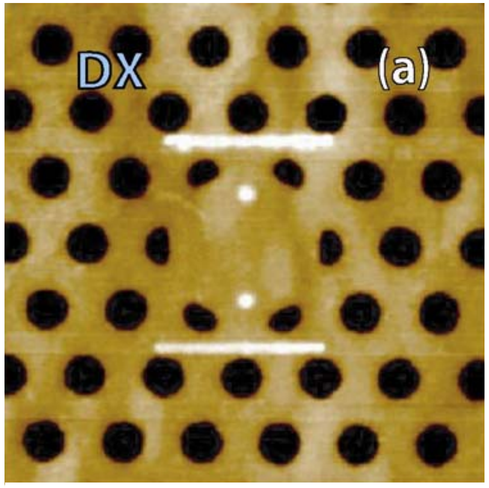


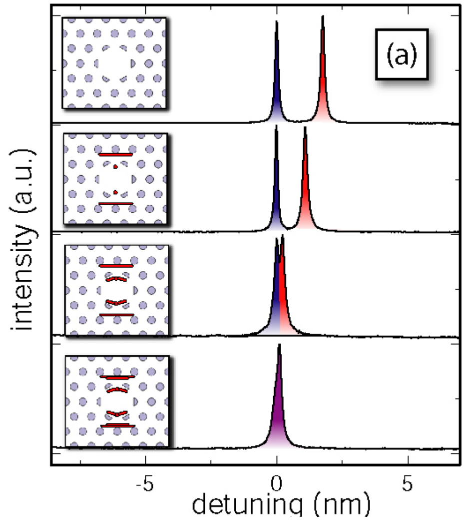
Polarization analysis of the two nearly-degenerate modes

- The observed mode-splitting ranges from 2 nm to ~ 0 nm.
- The Q values range from 5000 to 10000.

Power of nanotechnology: fine-tuning of cavity modes







By spatially selective oxidation of the PC membrane surface using AFM, we can change the relative energy spacing of the two cavity modes with a resolution < 100 μeV.

Future prospects and challenges

- Active positioning and digital etching should allow for essentially all cavity-QED tasks requiring a single emitter coupled to a single cavity mode.
- Using stacked QDs in a cavity, it is possible to solve the “spatial overlap” problem for 2 or 3 QDs in a single defect cavity. However, size non-uniformity of QDs would still limit the realisability of cavity-mediated interactions.
- Other challenges:

  i) Increasing the Q value of GaAs PC cavities below 1 μm;

  ii) <u>Confining light in sub-wavelength length scales</u>.
- Alternative systems for cavity-QED: microwave transitions, magnetic-dipole transitions, collective nuclear spin excitations…

Acknowledgements

- A. Badolato and K. Hennessy
- M. Winger, S. Gulde and D. Gerace, M. Atature, J. Dreiser (ETH Zurich)
- E. Hu and P. Petroff (UCSB)