Cavity QED with Photonic Band Gap and Pillar Resonators

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Stefan Strauf, Brian Gerardo, Antonio Badolato, Kevin Hennessy,
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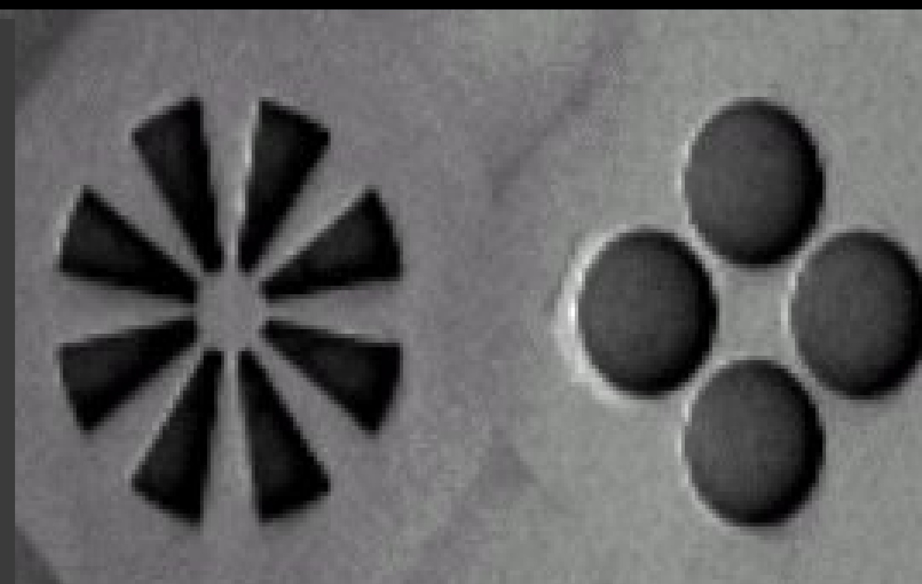
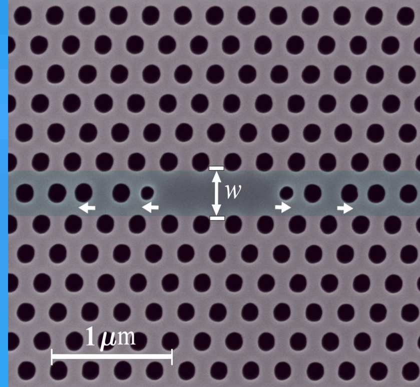
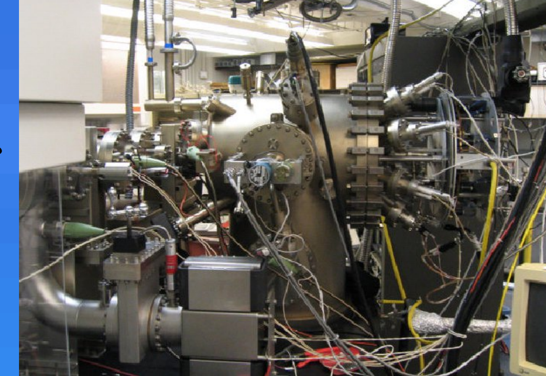
University of California, Santa Barbara



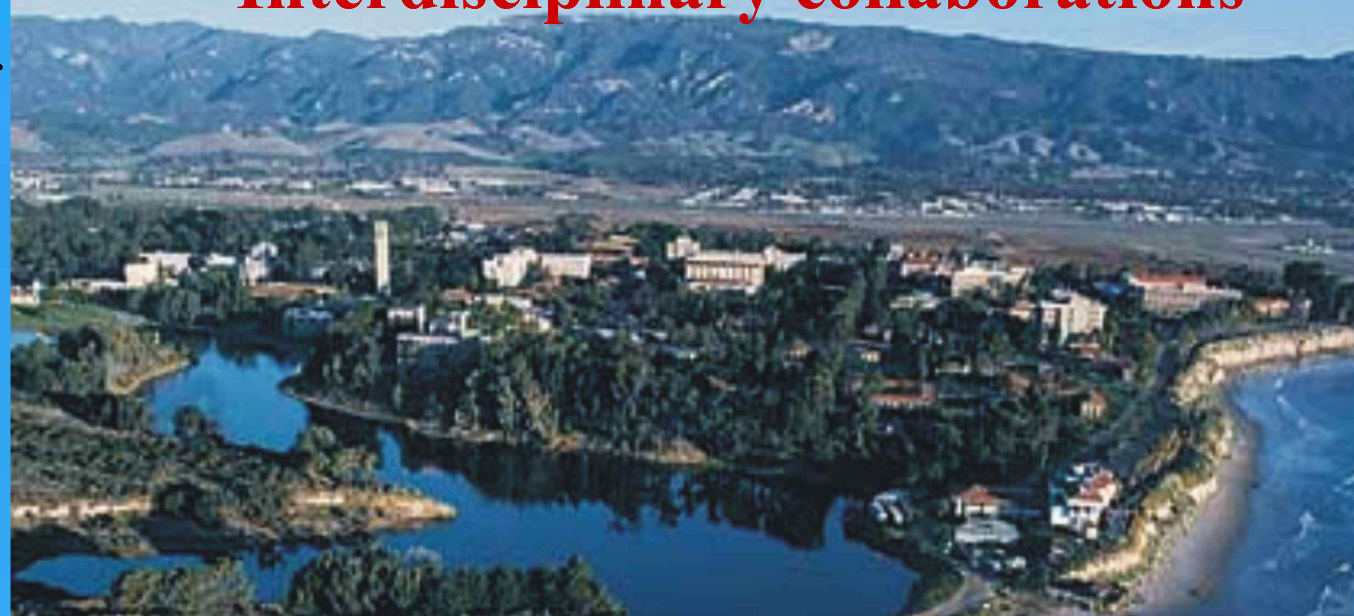
Eveline Hu



Pierre Petroff



Interdisciplinary collaborations



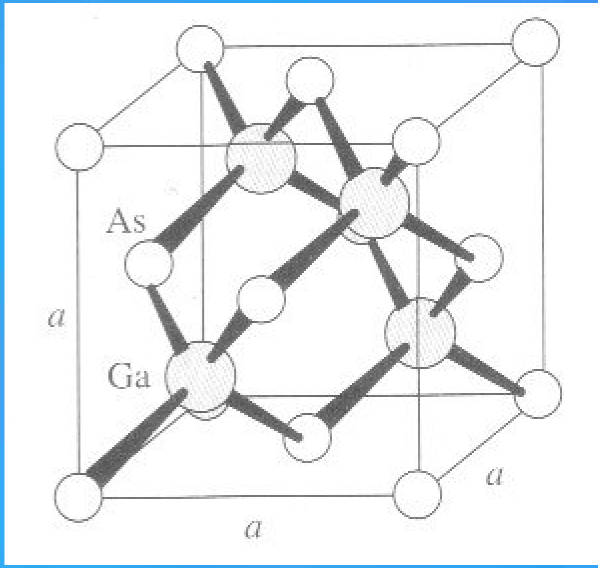
Dirk Bouwmeester

Larry Coldren

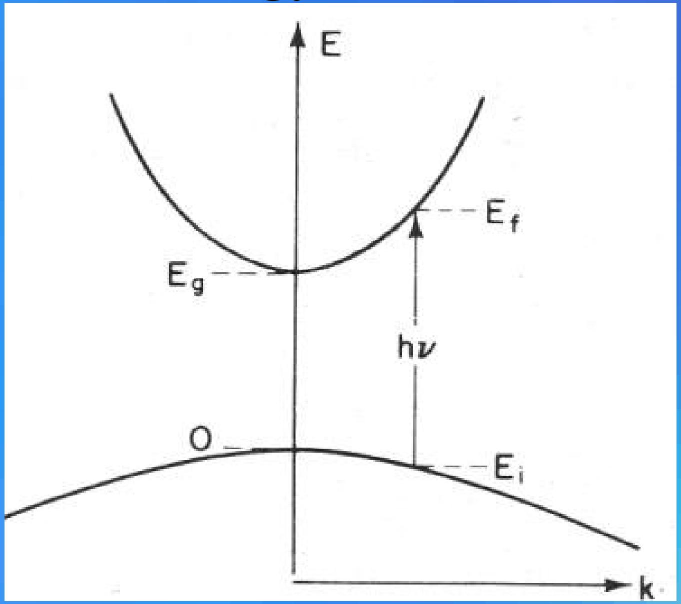
Quantum Dots

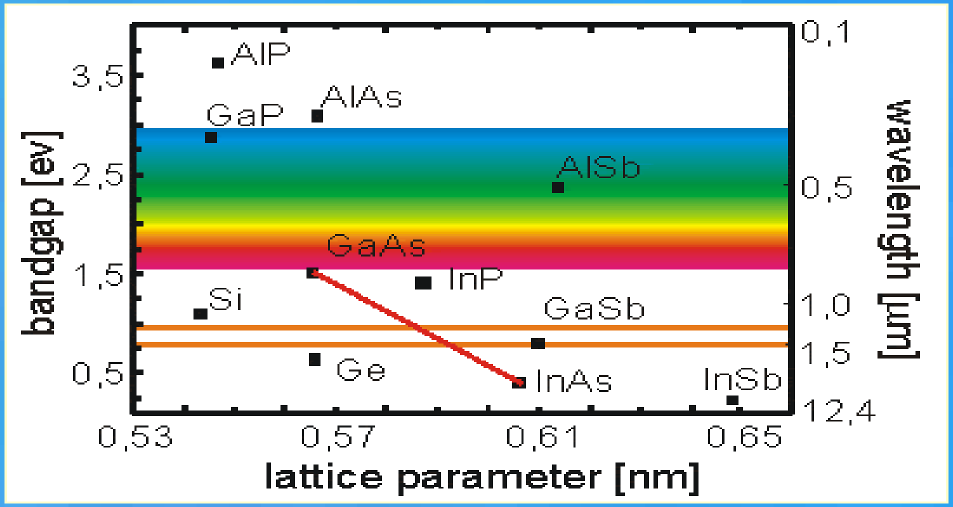
Semiconductors

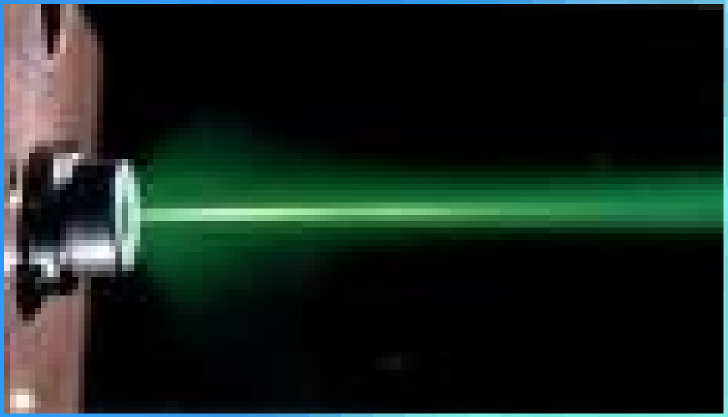
Periodic structure



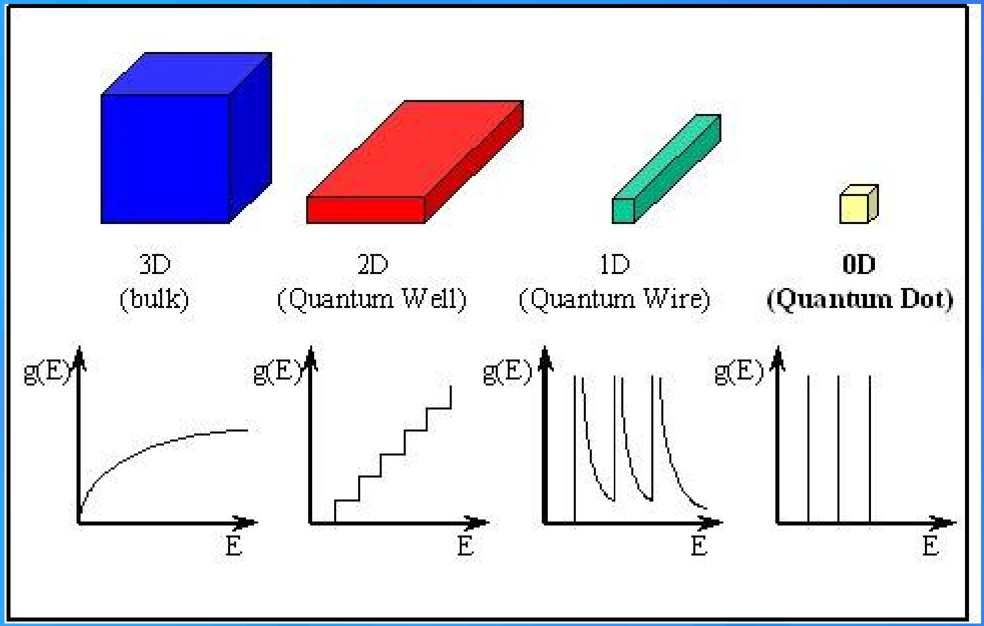
Energy bands



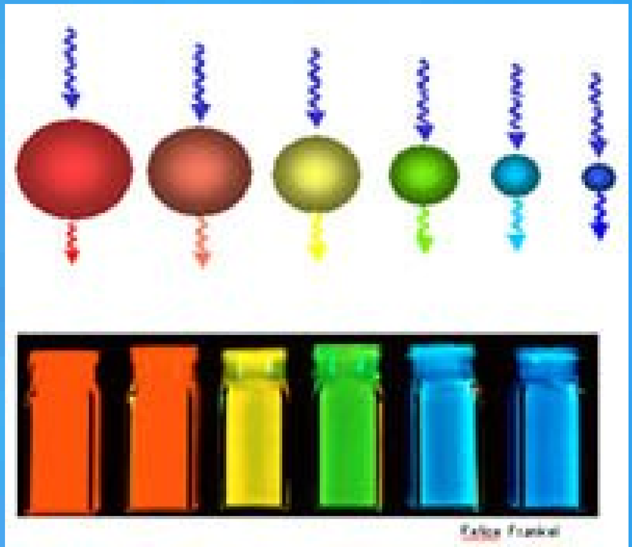




Quantum dots – artificial atoms

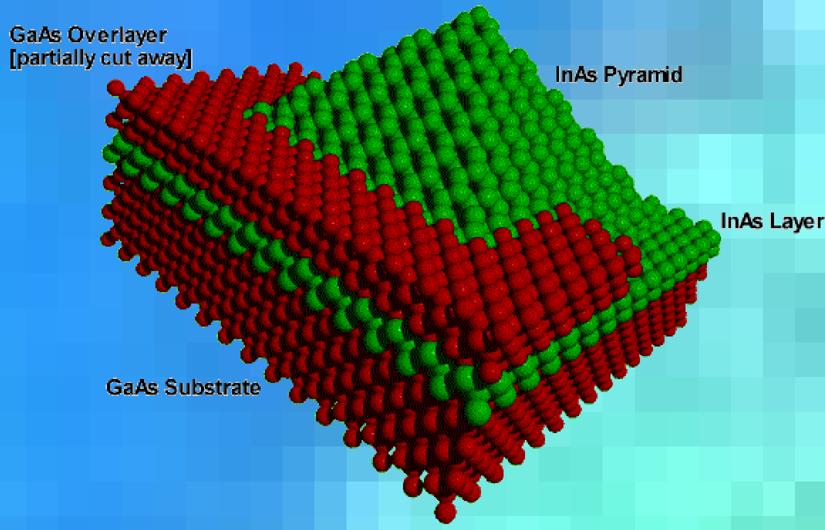


Colloidal QDs

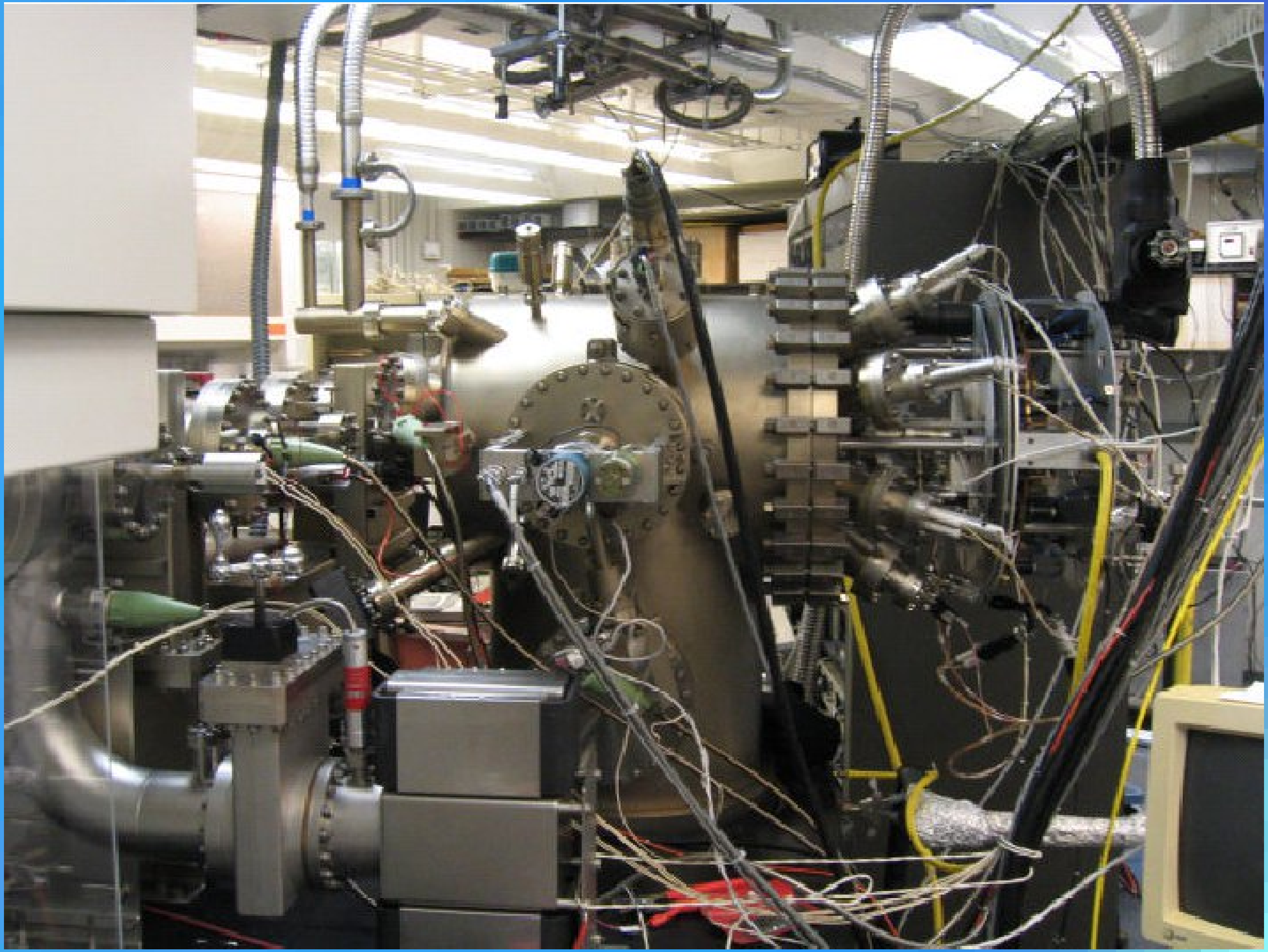


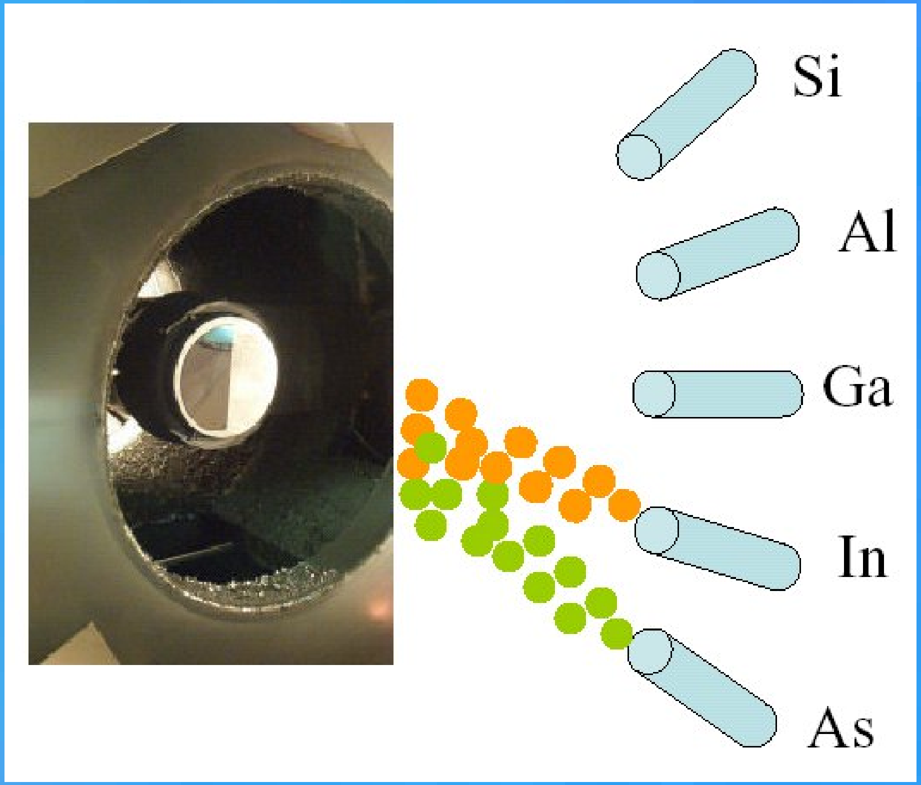
Size
1-20 nm

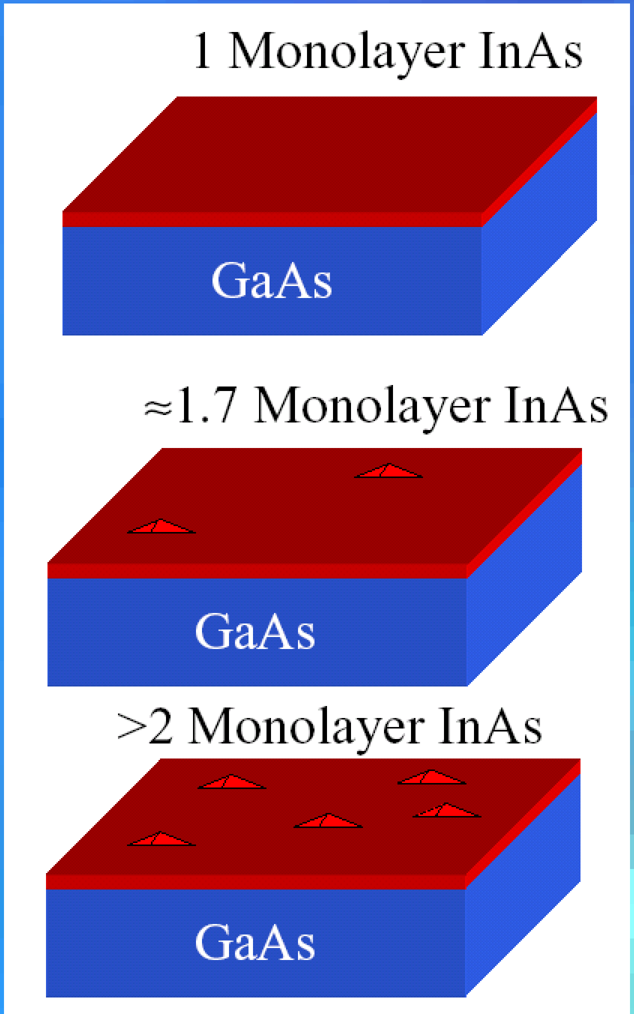
Epitaxial QDs



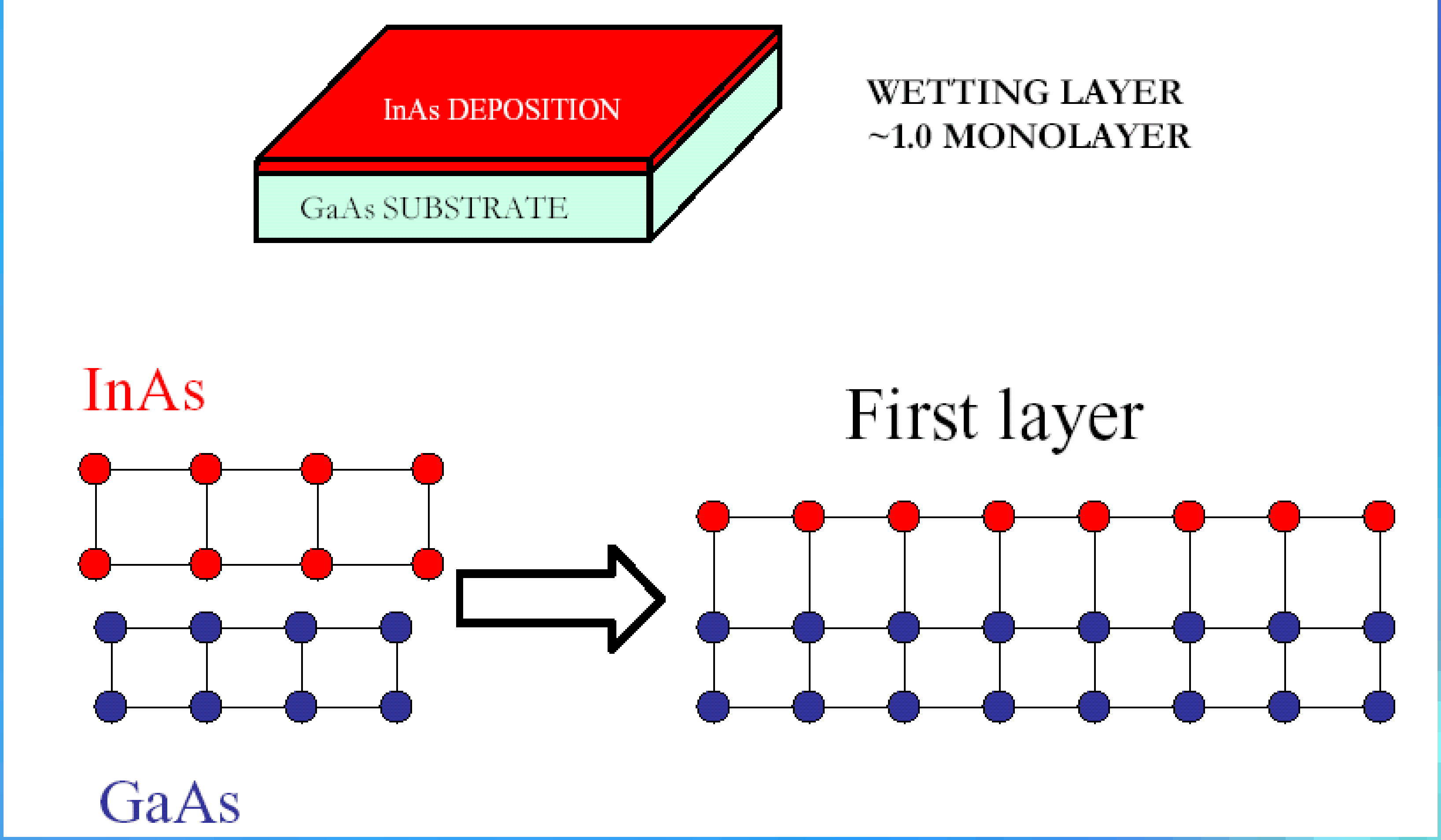
Molecular Beam Epitaxy growth (MBE)

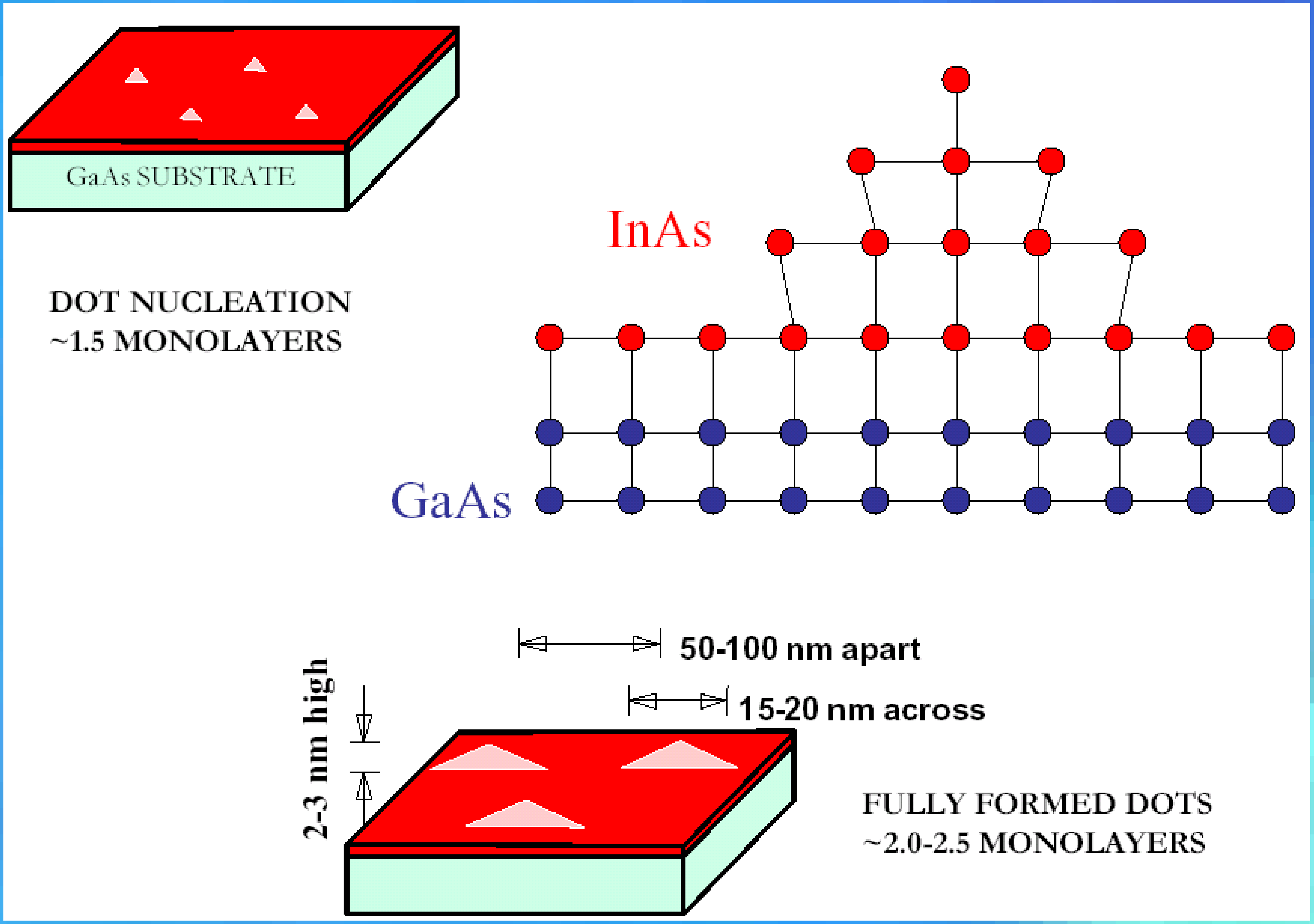



Si
Al
Ga
In
As

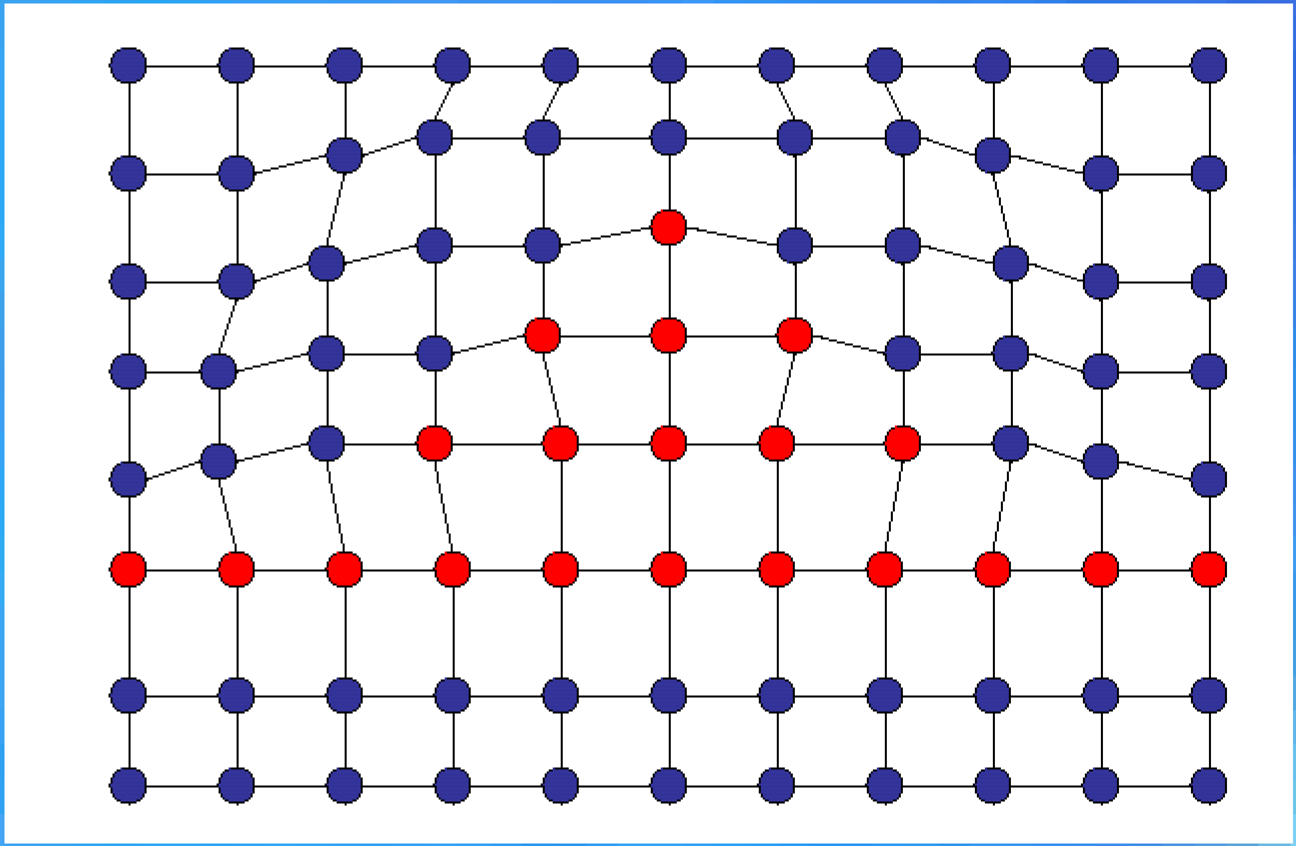

1 Monolayer InAs
GaAs
≈1.7 Monolayer InAs
GaAs
>2 Monolayer InAs
GaAs

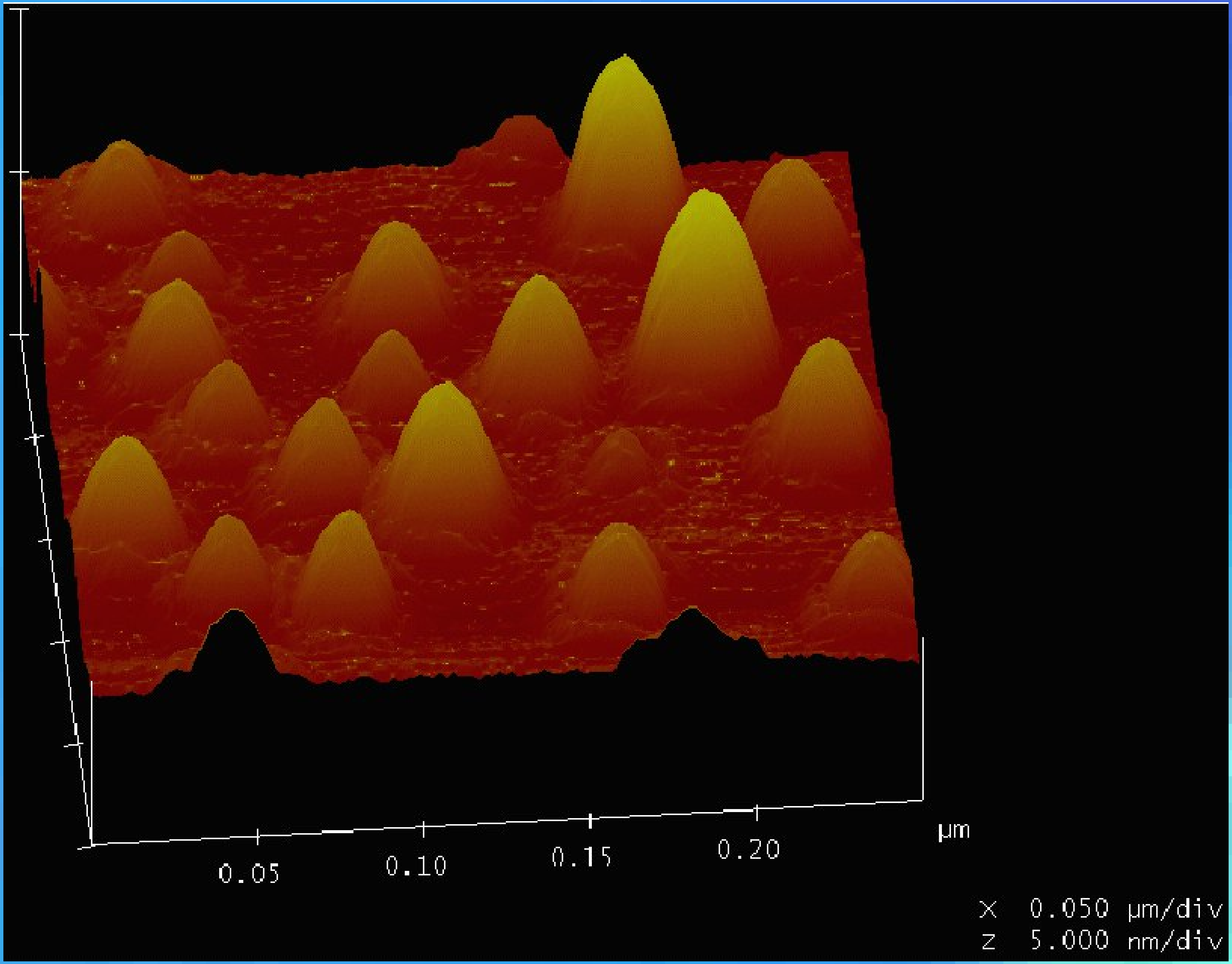
Wetting layer



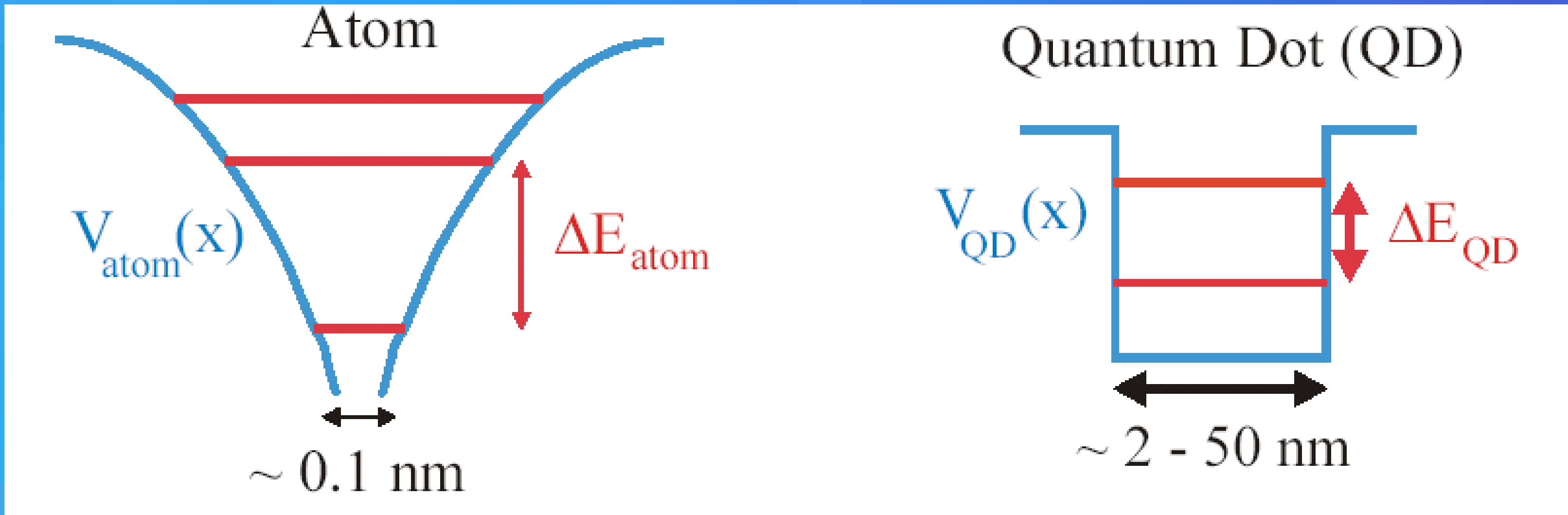


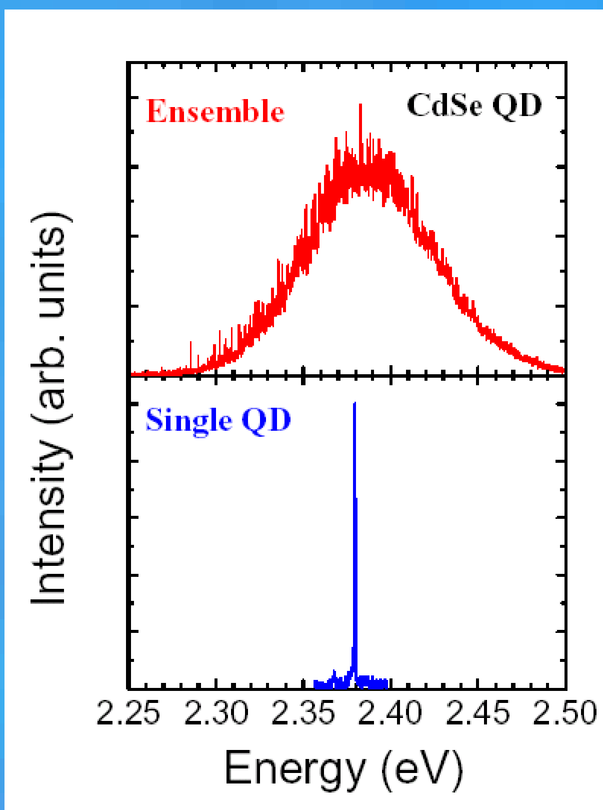
GaAs SUBSTRATE
DOT NUCLEATION
~1.5 MONOLAYERS
InAs
GaAs
50-100 nm apart
15-20 nm across
2-3 nm high
FULLY FORMED DOTS
~2.0-2.5 MONOLAYERS

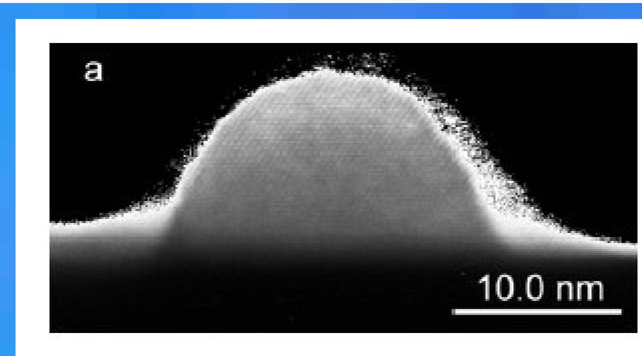




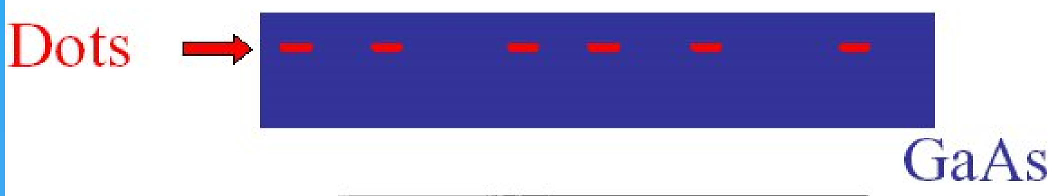
0.05
0.10
0.15
0.20
µm
X 0.050 µm/div
Z 5.000 nm/div

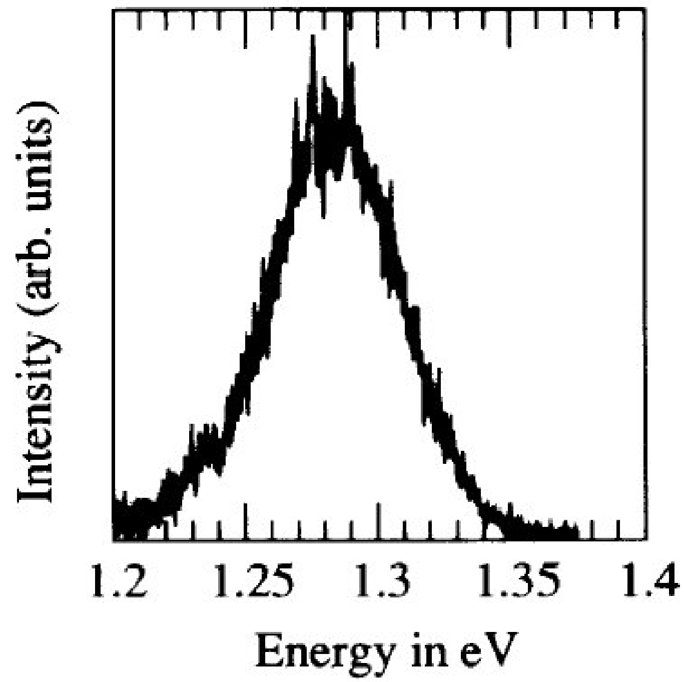

Atom
$V_{atom}(x)$
ΔE_{atom}
~ 0.1 nm
Quantum Dot (QD)
$V_{QD}(x)$
ΔE_{QD}
~ 2 - 50 nm


Ensemble
CdSe QD
Single QD
Intensity (arb. units)
2.25 2.30 2.35 2.40 2.45 2.50
Energy (eV)


a
10.0 nm

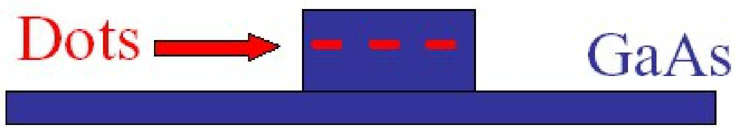
Large area

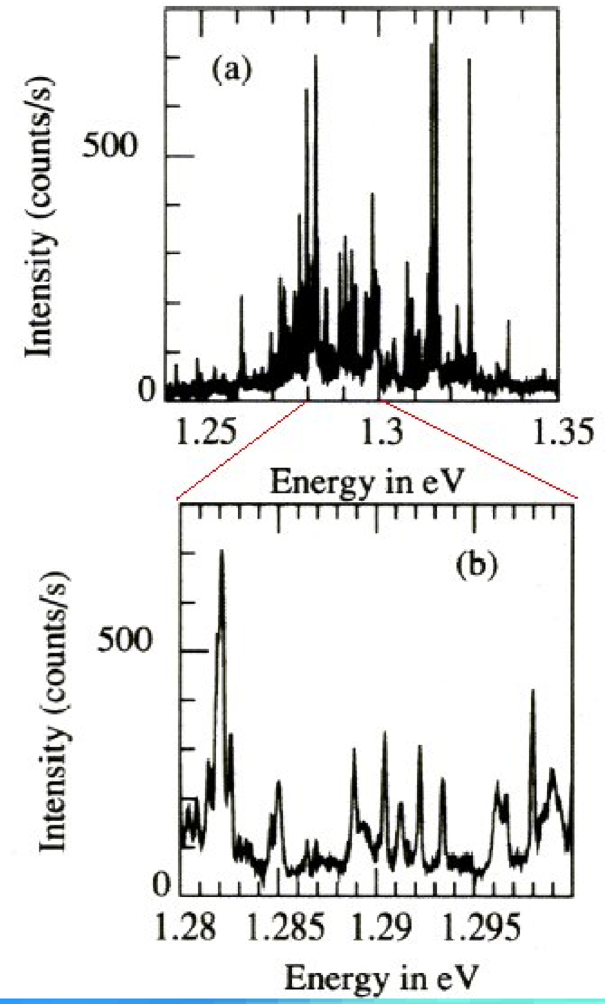


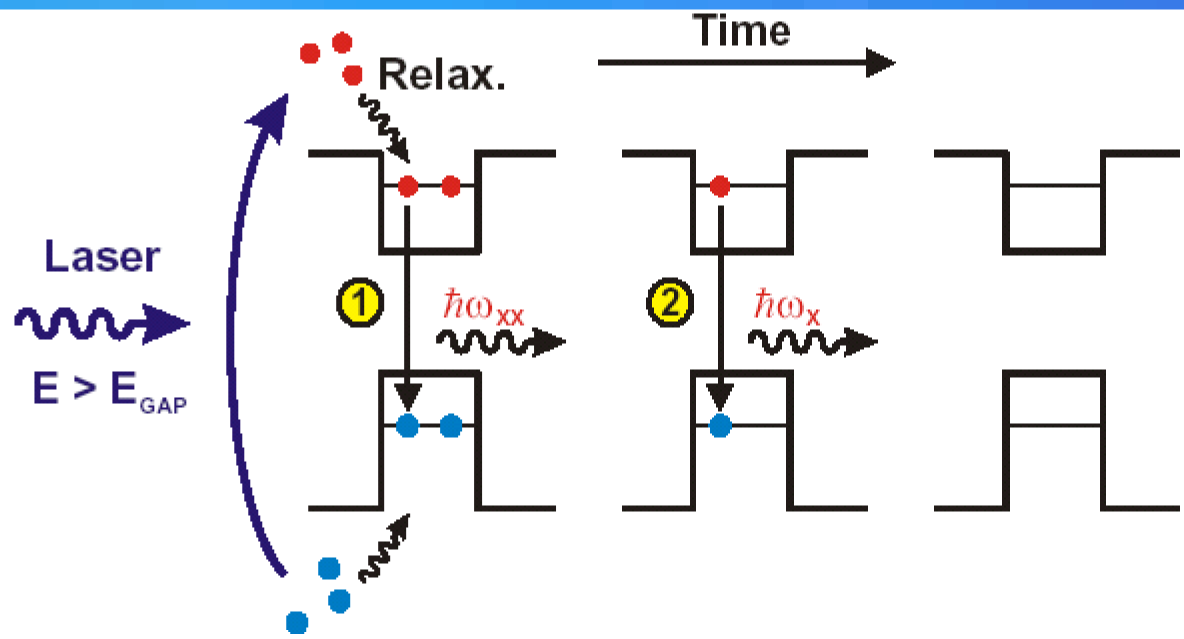


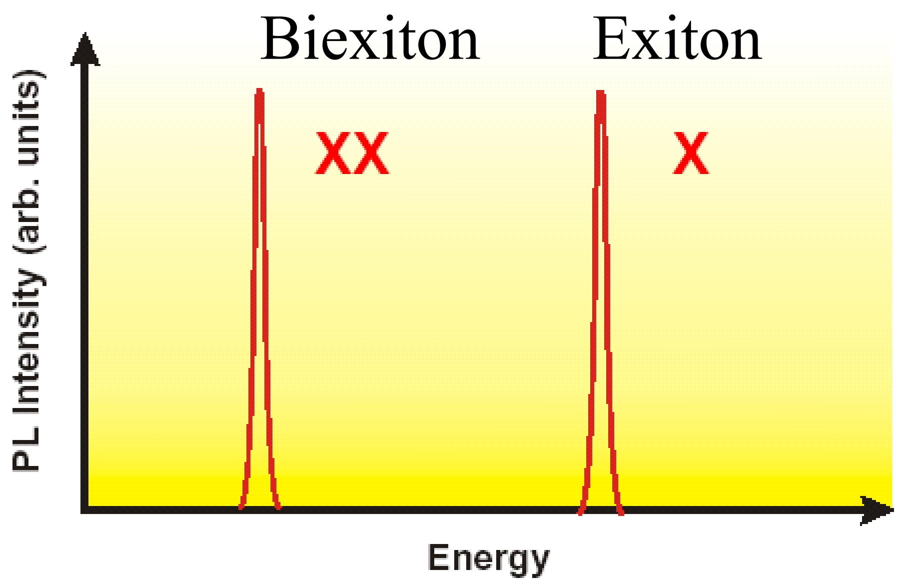
J.-Y. Marzin, J.-M. Gérard, A. Izraël, and D. Barrier, Phys. Rev. Lett. **73**, 716 (1994).

Small mesa



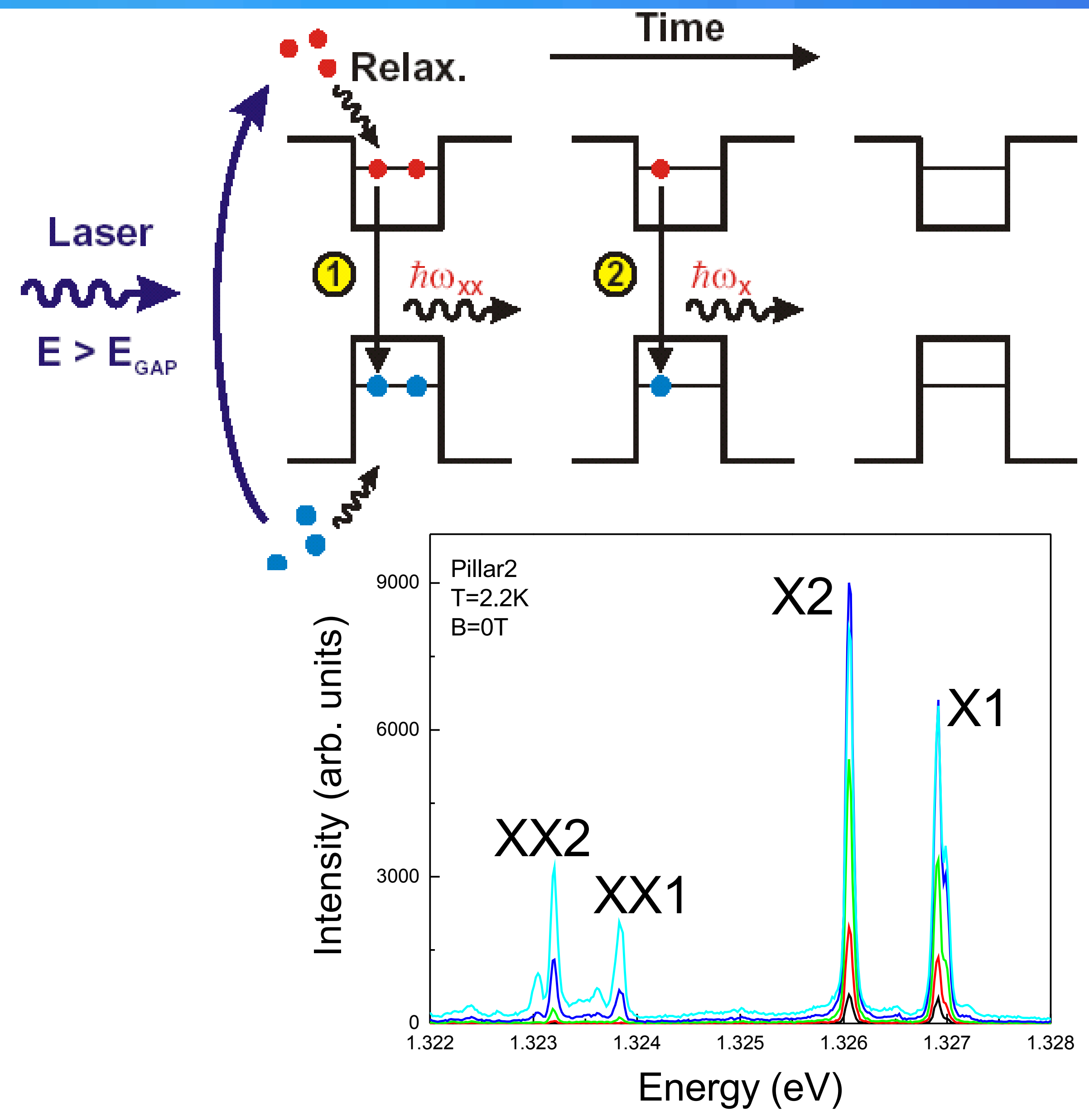






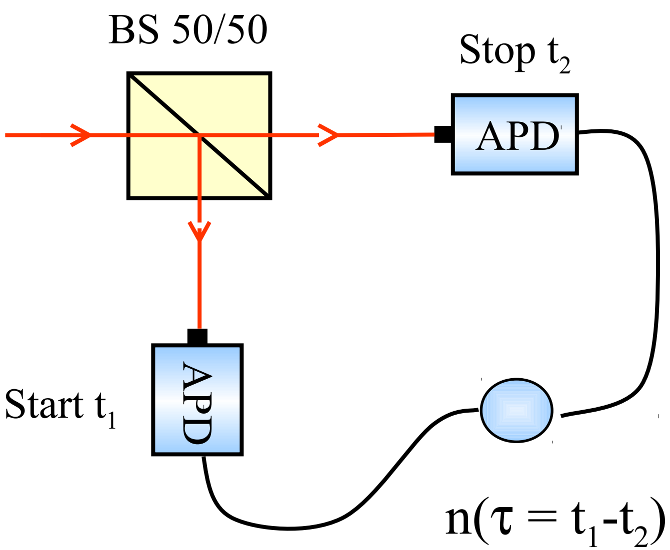
due to Coulomb interaction:

$$\hbar\omega_{XX} \neq \hbar\omega_X$$



Time
Relax.
Laser
E > E_GAP
1
ħω_XX
2
ħω_X
Pillar2
T=2.2K
B=0T
X2
X1
XX2
XX1
Intensity (arb. units)
Energy (eV)
9000
6000
3000
0
1.322
1.323
1.324
1.325
1.326
1.327
1.328

Photon correlation spectroscopy



photon correlation function

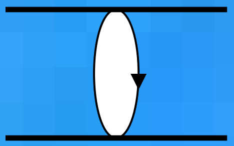
$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau) \rangle}{\langle I(t)^2 \rangle}$$

ensemble emission

classical light (laser):

$g^{(2)}(\tau) = 1$

single quantum emitter

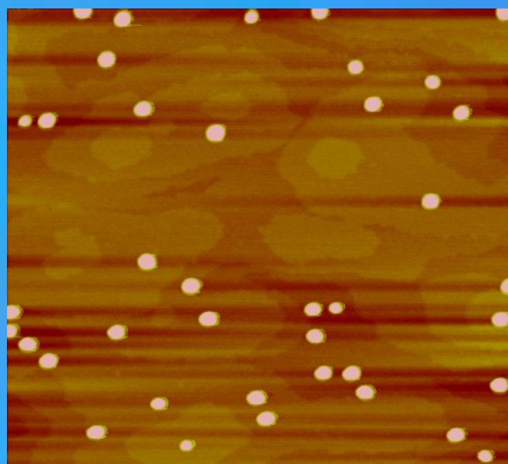


nonclassical light (photon antibunching):

$g^{(2)}(\tau=0) = 0$

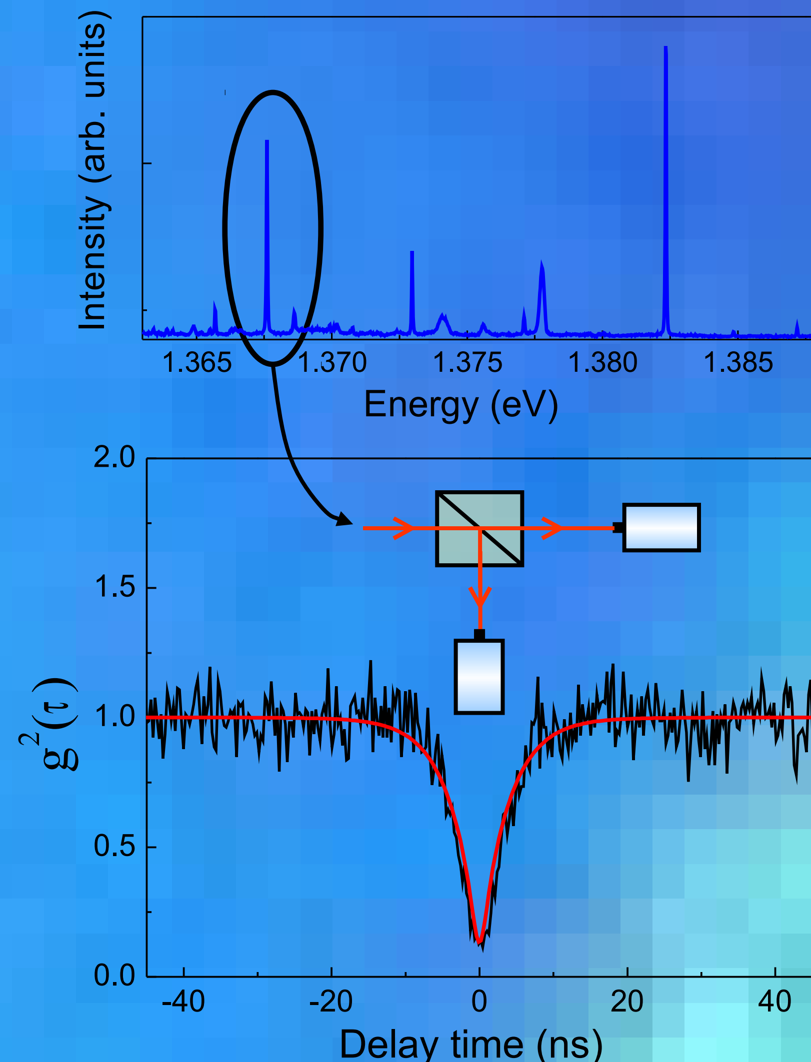
Individual quantum dots

InAs quantum dots
embedded in **GaAs** matrix



1µm x 1µm AFM

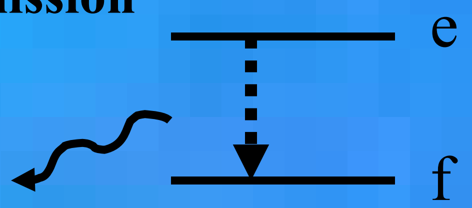
- Dot size: 10-20 nm
- Emission: 900-950 nm
- Density gradient



Photon antibunching

Quantum Dots in Cavities

Spontaneous emission

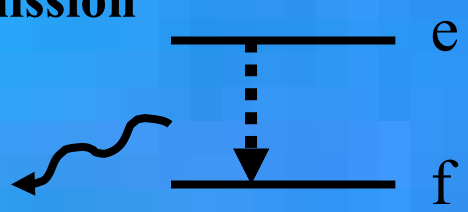


$$E_e - E_f = \hbar\omega$$

For a single mode the rms electric-field amplitude is $E_{vac} = \sqrt{\dfrac{\hbar\omega}{2\varepsilon V}}$.

Coupling to this mode is characterized by the Rabi frequency $\Omega = \dfrac{DE_{vac}}{\hbar}$.

Spontaneous emission



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Coupling to this mode is characterized by the Rabi frequency $\Omega = \dfrac{DE_{vac}}{\hbar}$.

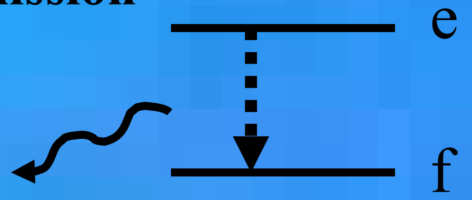
The probability of photon emission per unit time (Einstein A coefficient) is given by

$\Gamma_0 = 2\pi\Omega^2 \dfrac{\rho_0(\omega)}{3}$ with the mode density $\rho_0(\omega) = \omega^2 V/\pi^2 c^3$.

The probability to find the system at time t in state e (system prepared in e at t=0) is

$$P_e(t) = e^{-\Gamma_0 t}.$$

Spontaneous emission



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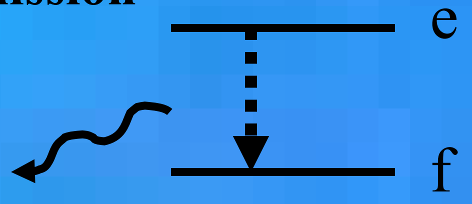
In an optical cavity (quality factor $Q = \omega / \Delta\omega_c$) the mode density and mode volume are drastically changed.

Off resonance: inhibition of SE

Spontaneous emission



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For a single mode the rms electric-field amplitude is $E_{vac} = \sqrt{\dfrac{\hbar\omega}{2\varepsilon V}}$.

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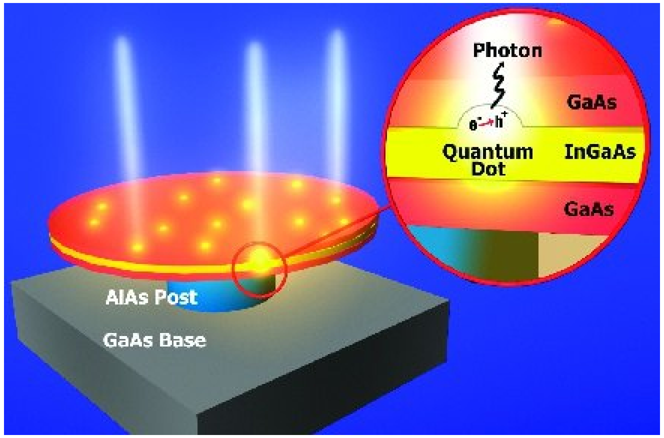
$$P_e(t) = e^{-\Gamma_0 t} .$$

In an optical cavity (quality factor $Q = \omega / \Delta\omega_c$) the mode density and mode volume are drastically changed. **On resonance enhancement:** $\Gamma_{cav} \cong \Gamma_0 \dfrac{Q\lambda^3}{V}$

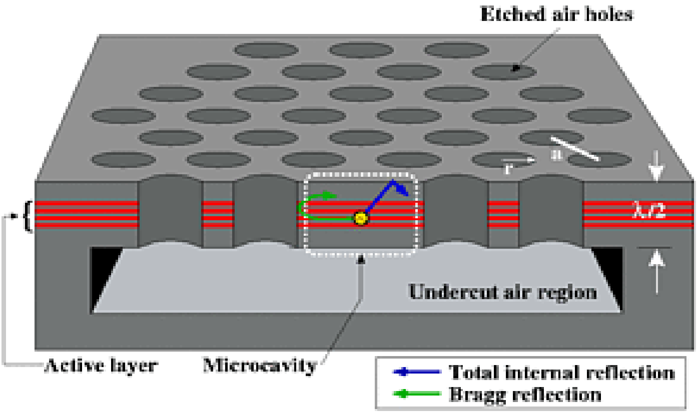
Purcell factor

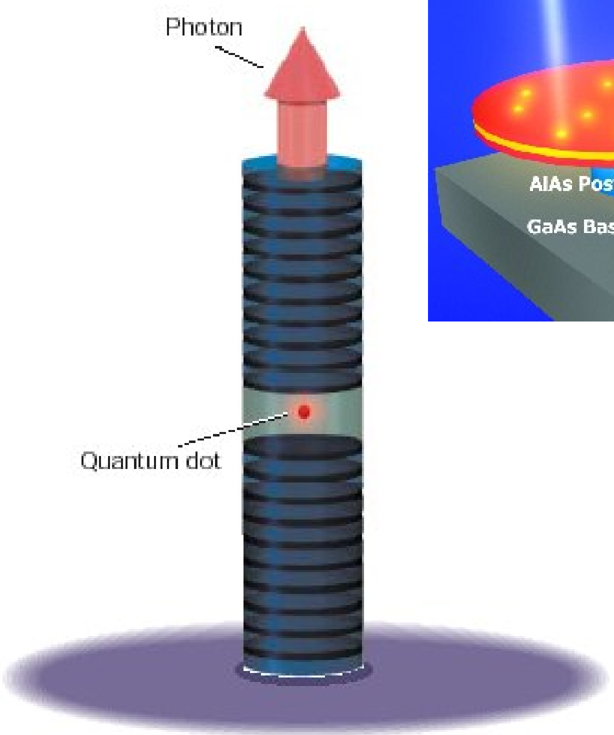
Optical microcavities

Microdisc



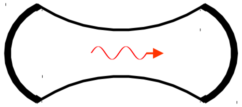
Photonic crystal





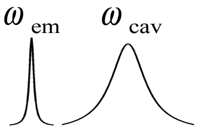
Micropillar

$$F_p = \frac{3}{4\pi^2}\frac{Q}{v_{eff}} \cdot \frac{\rho(\omega_{em})}{\rho(\omega_{cav})} \cdot \frac{E^2(r)}{E^2_{max}}$$

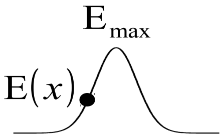


optical cavity

[>1000]



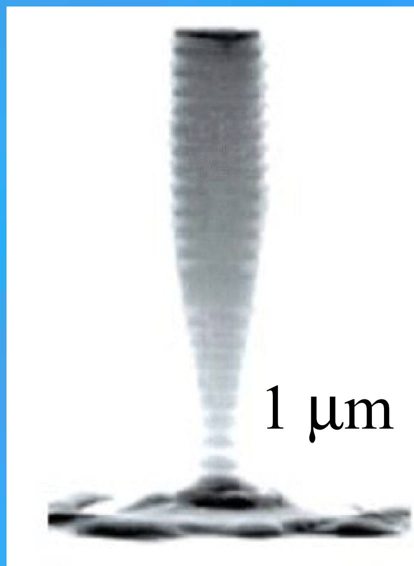
spectral resonance



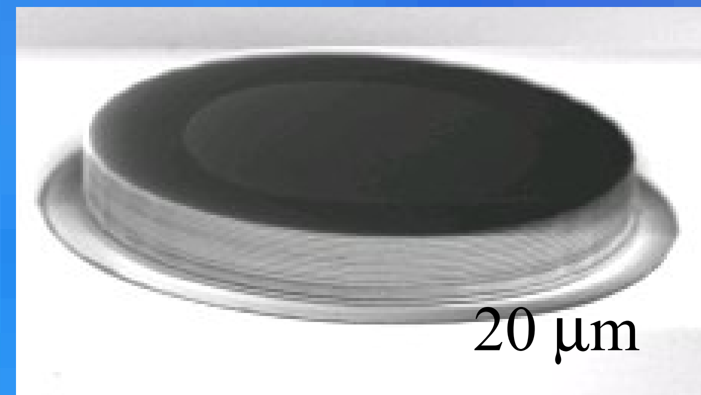
emitter location

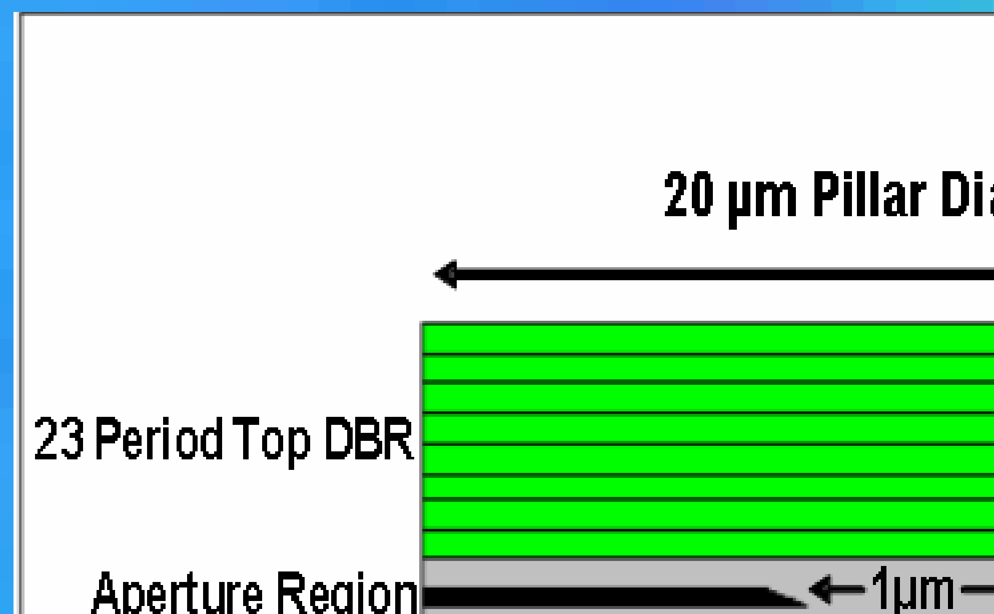
[0-1]

Oxide apertured micropillars



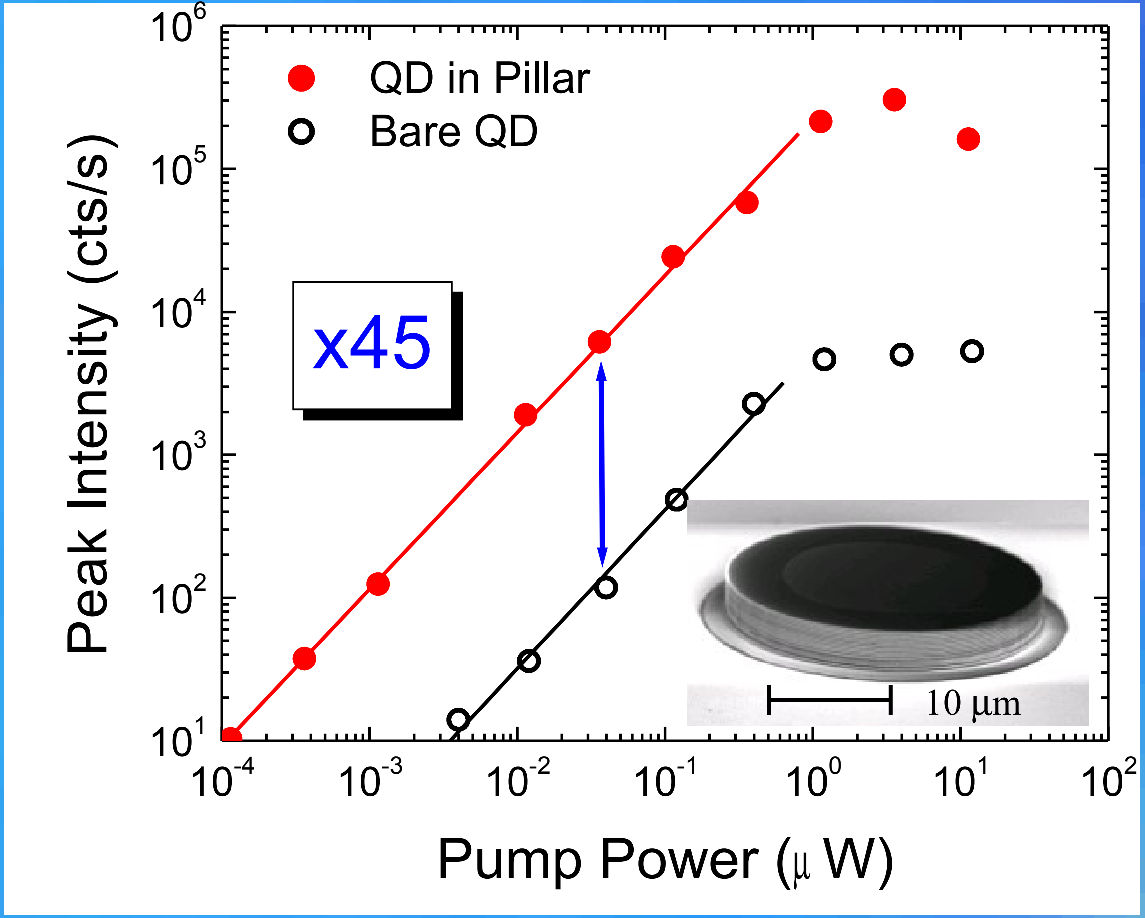
M. Pelton et al.,
PRL 2002





N. G. Stoltz, et al.

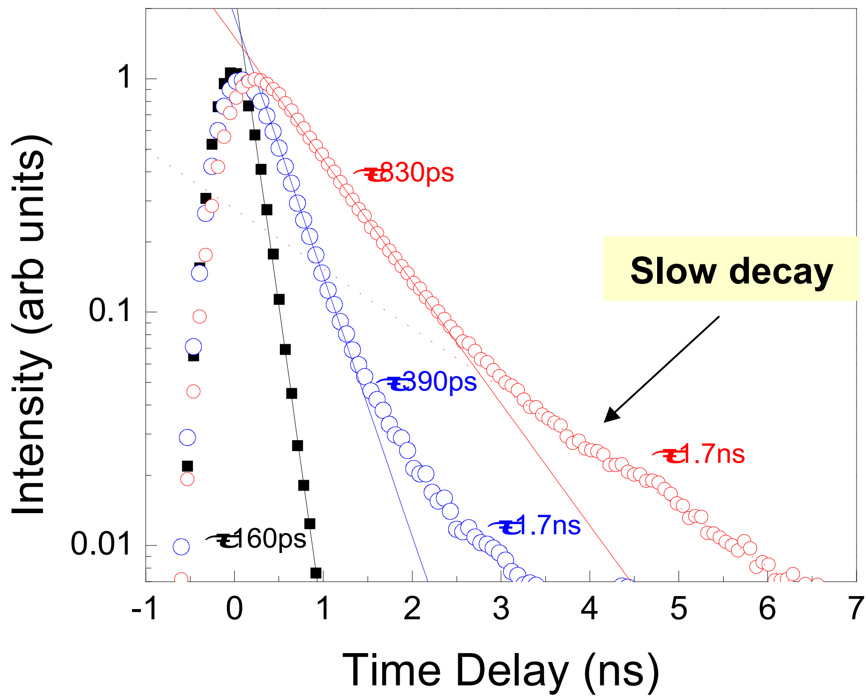
Enhanced light extraction



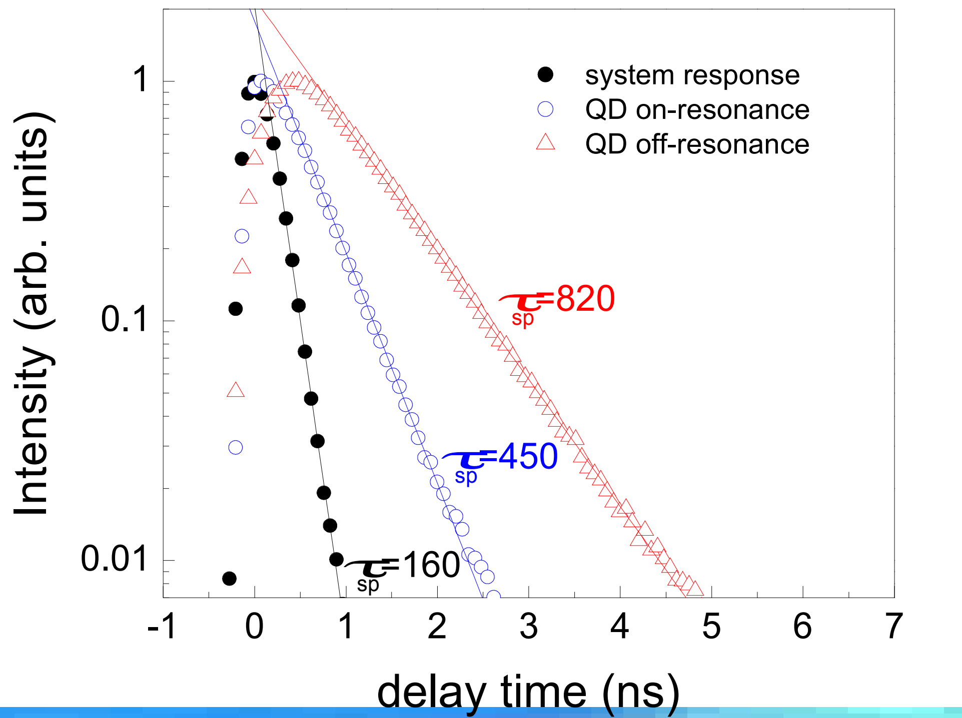
45 times enhancement of single photon stream emitted by a **single QD**

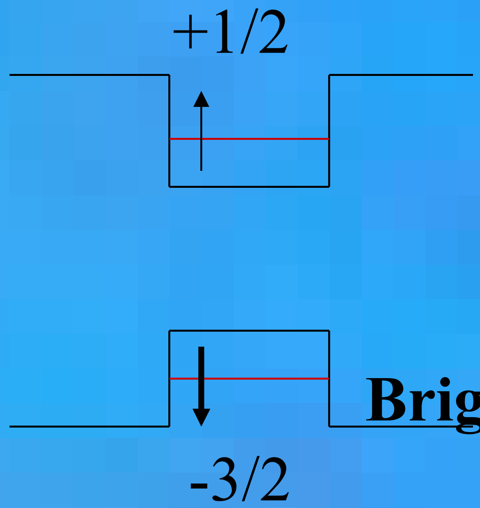
Two types of results

Type 1

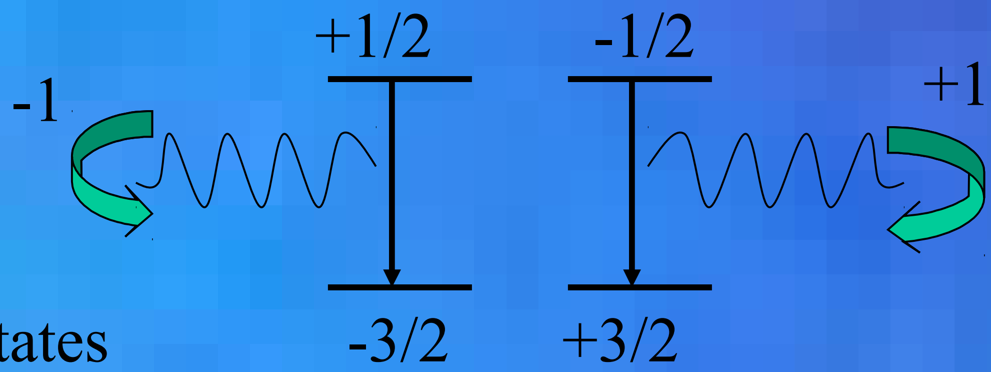


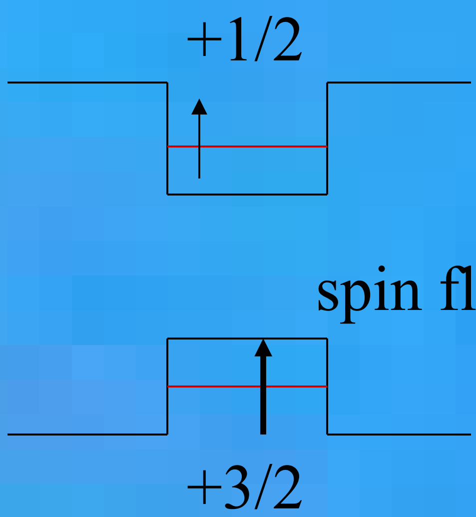
Type 2



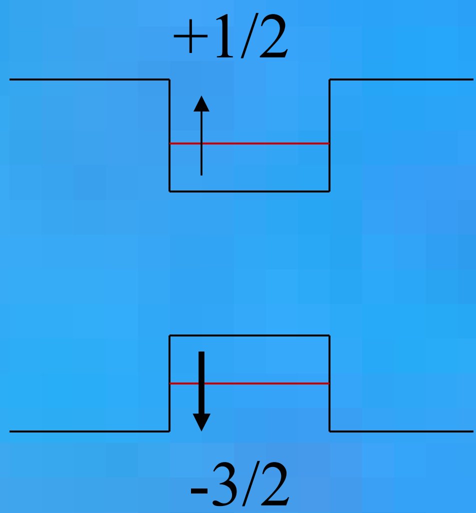


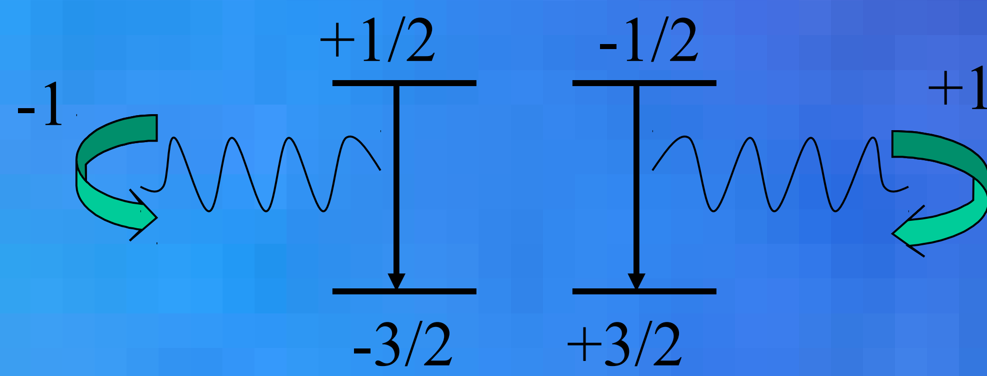
Bright states

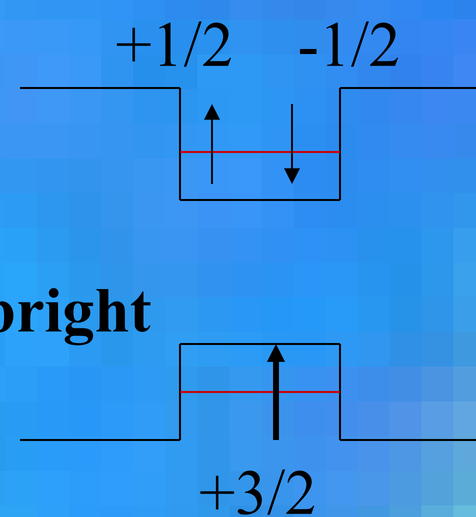




spin flip gives **Dark** state



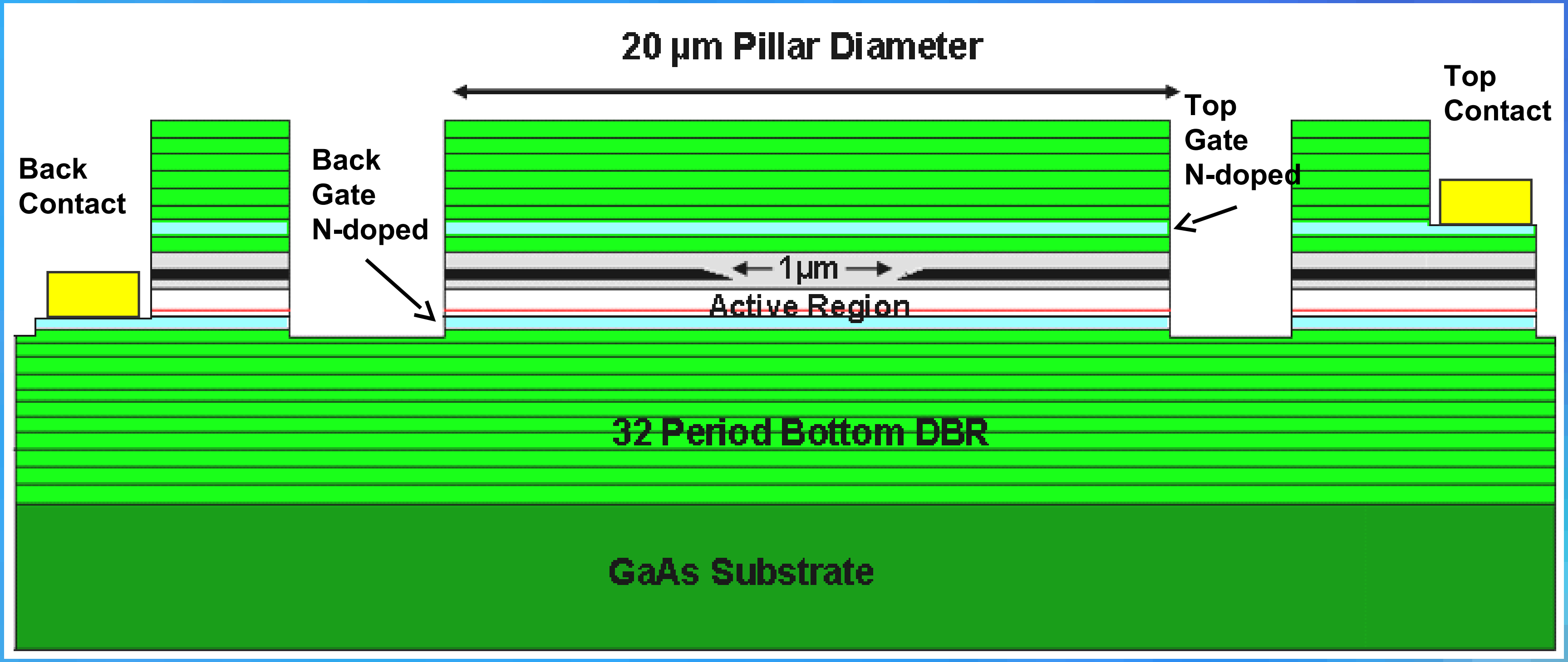


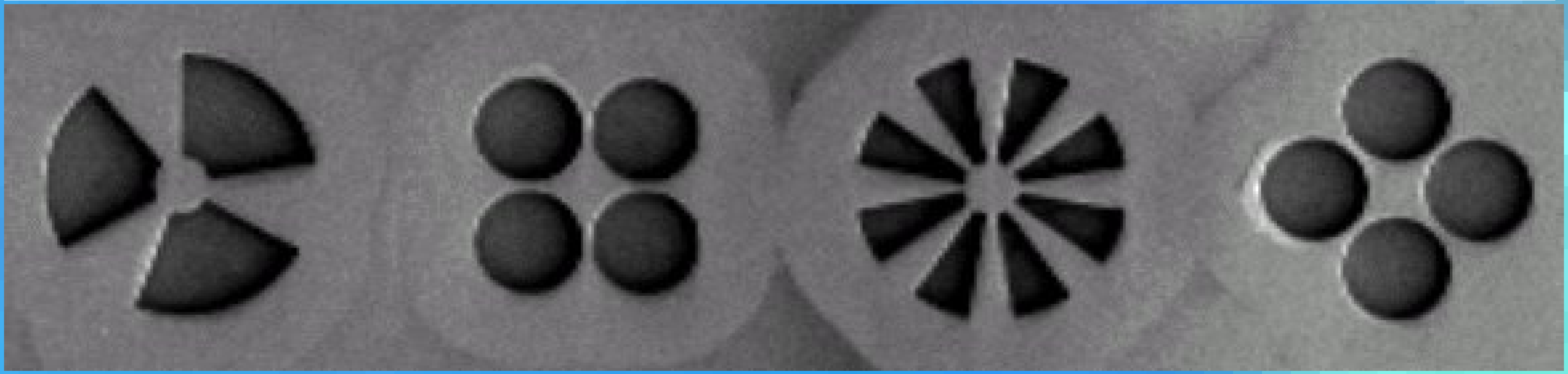


Add single electron

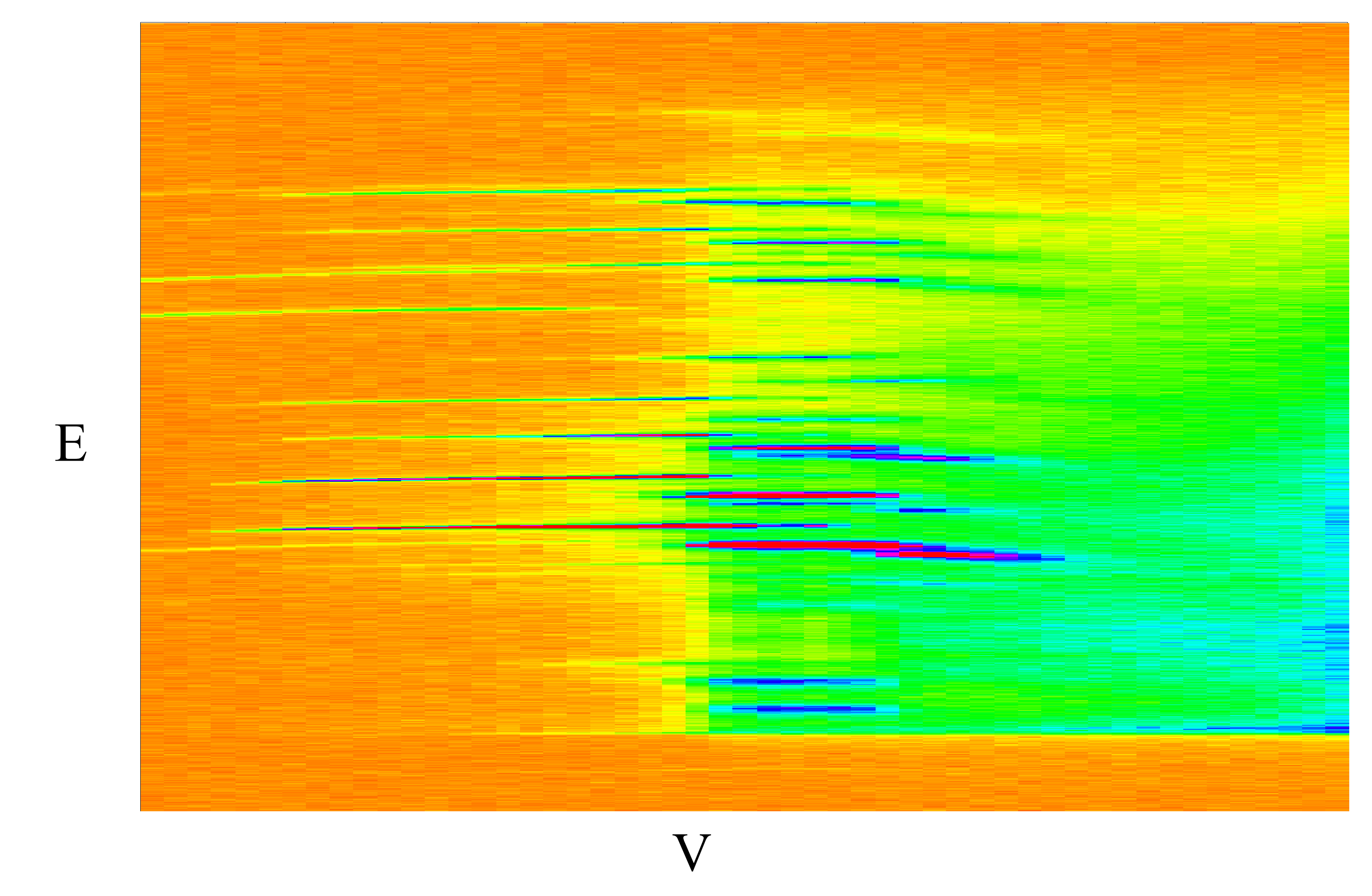
Trion state, always **bright**

Single Photon Source with integrated gates

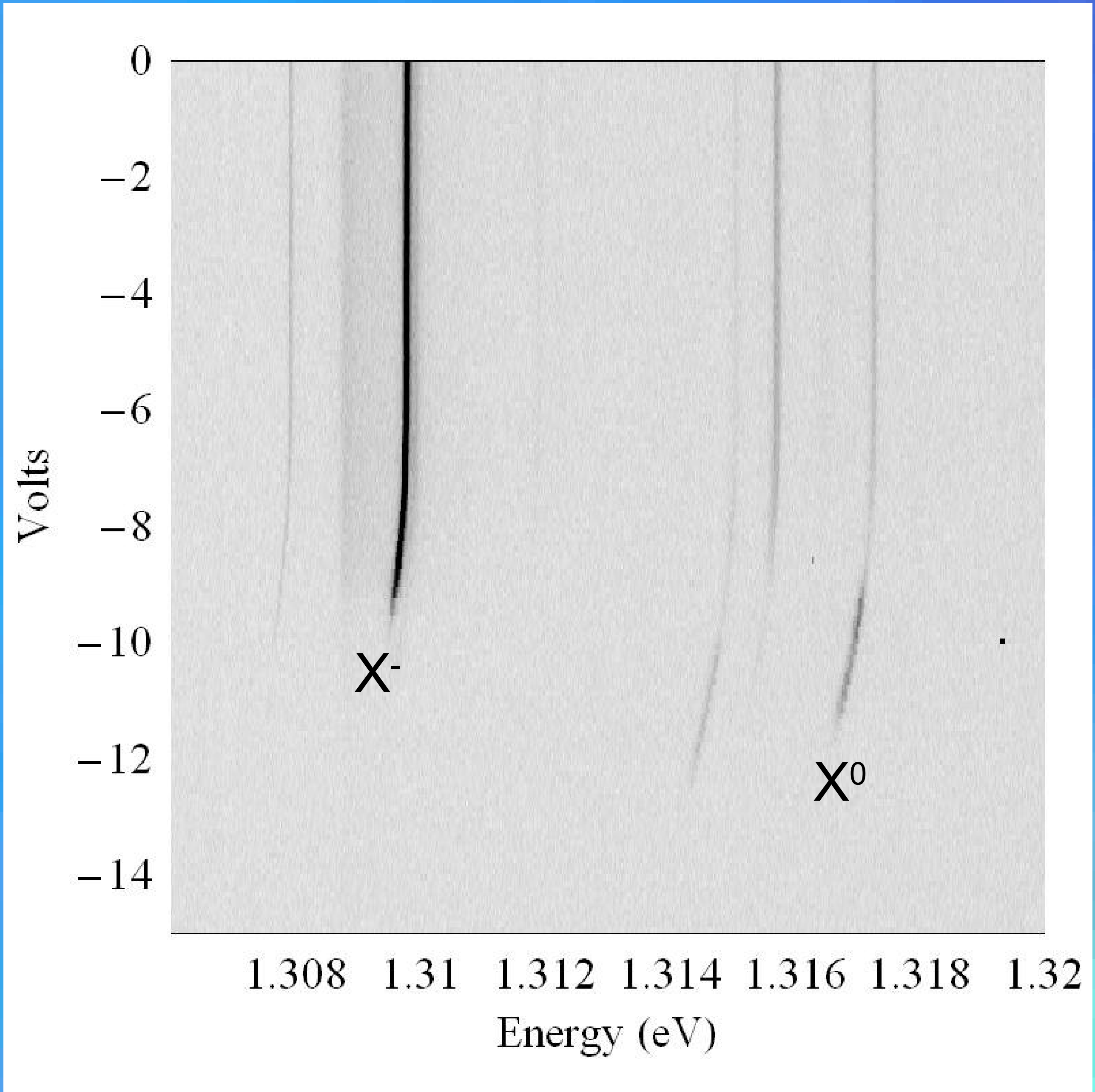




Charge control outside cavity region

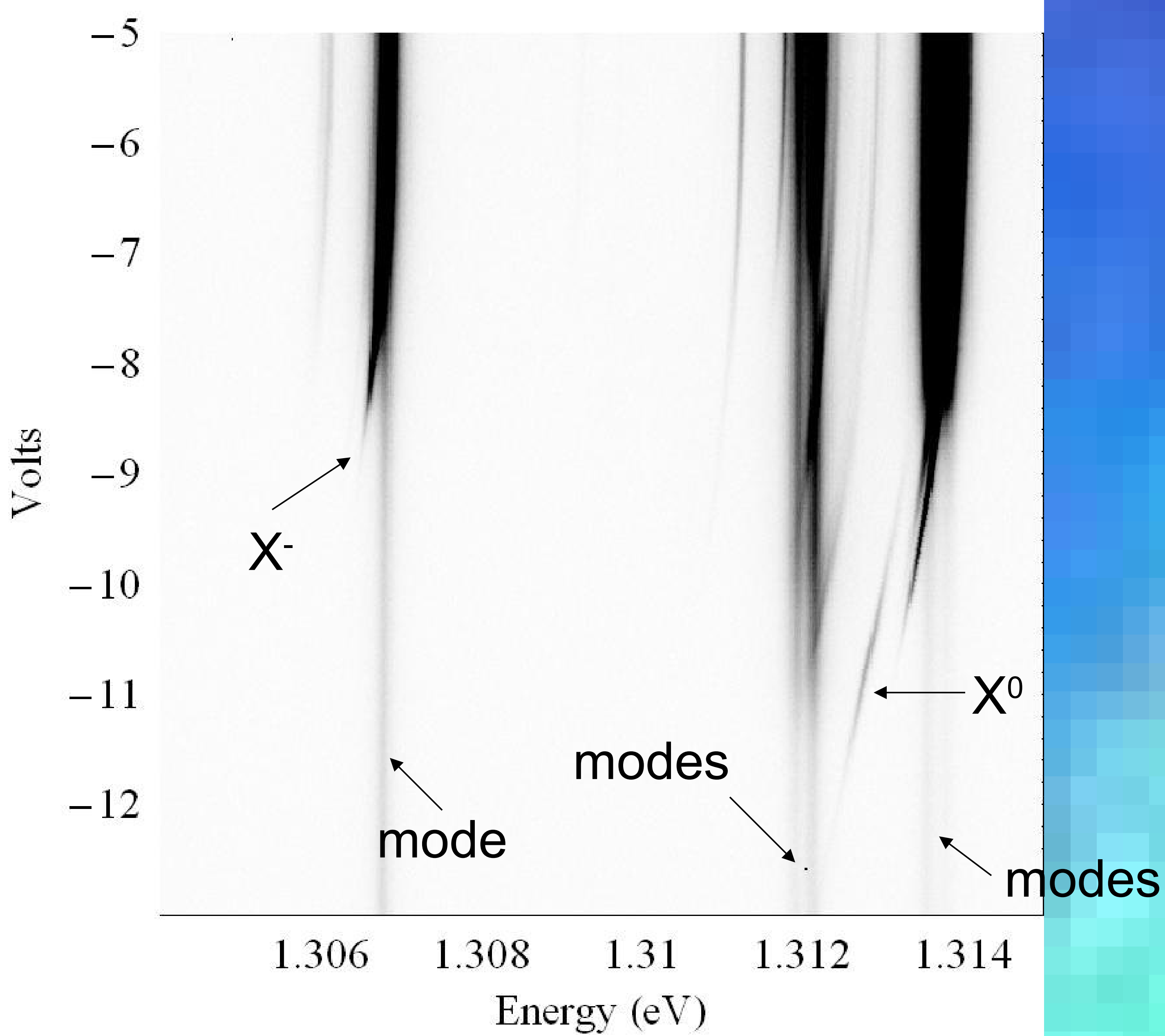


outside



0
−2
−4
−6
−8
−10
−12
−14
Volts
X^-
X^0
1.308 1.31 1.312 1.314 1.316 1.318 1.32
Energy (eV)

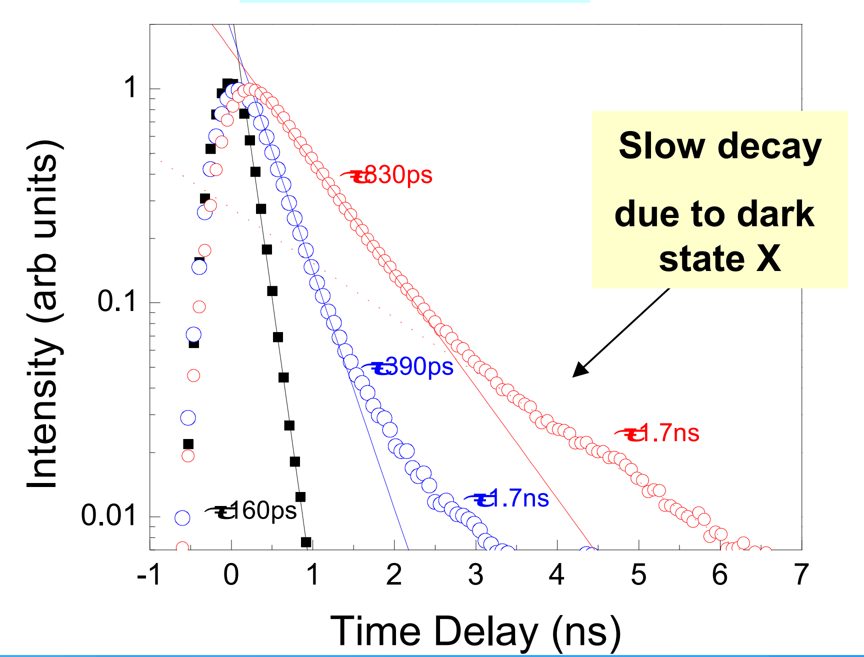
inside



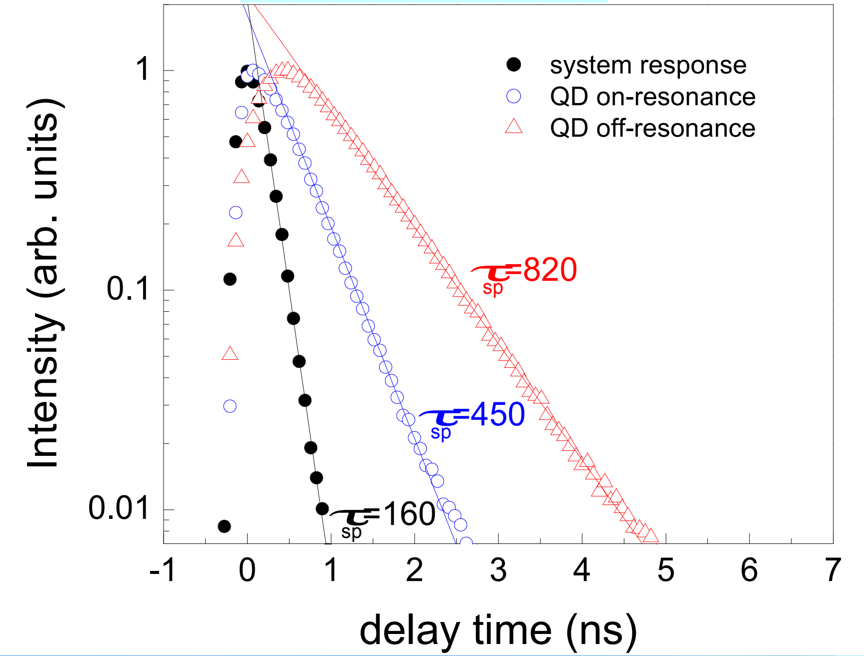
−5
−6
−7
−8
−9
−10
−11
−12
Volts
X-
mode
modes
X0
modes
1.306
1.308
1.31
1.312
1.314
Energy (eV)

A neutral and a charged QD

A neutral QD



A charged QD

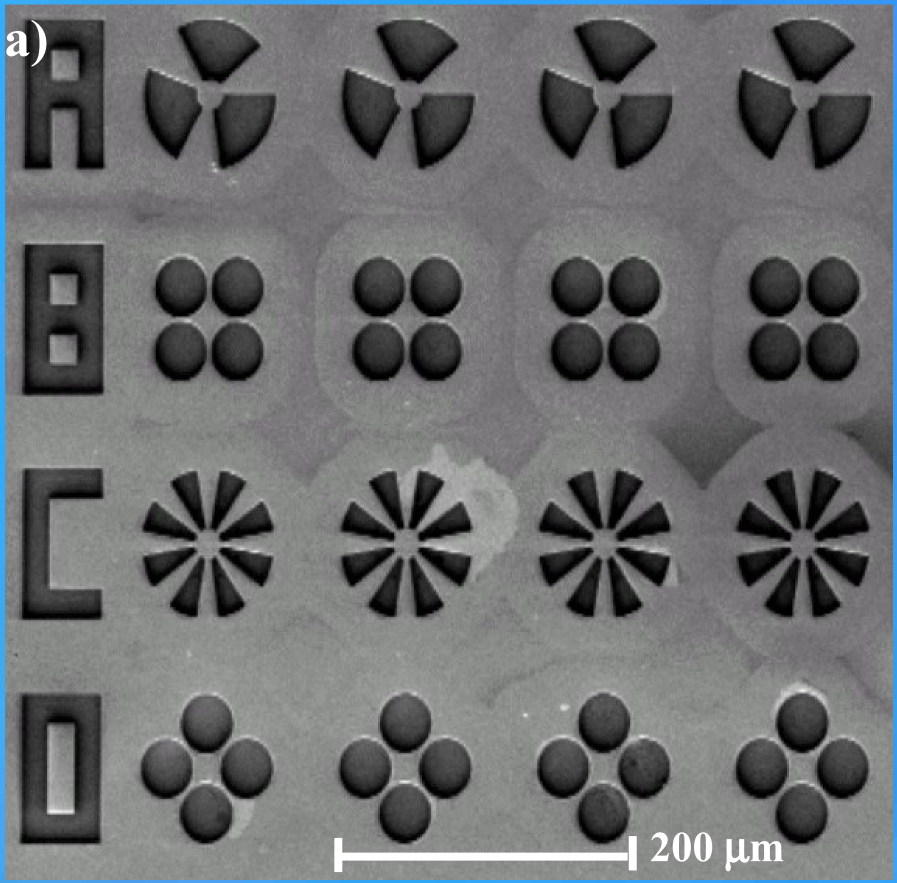


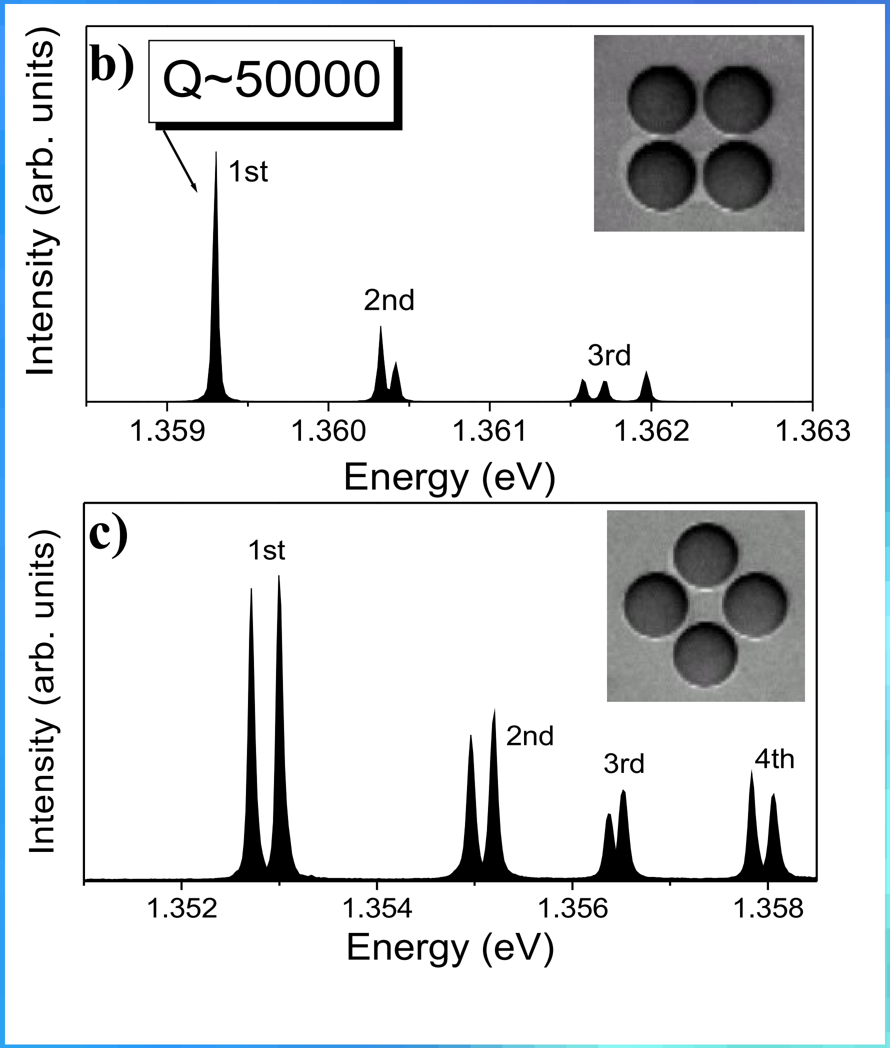
fs probe	cw probe
2.8/19 MHz	3.2/21 MHz

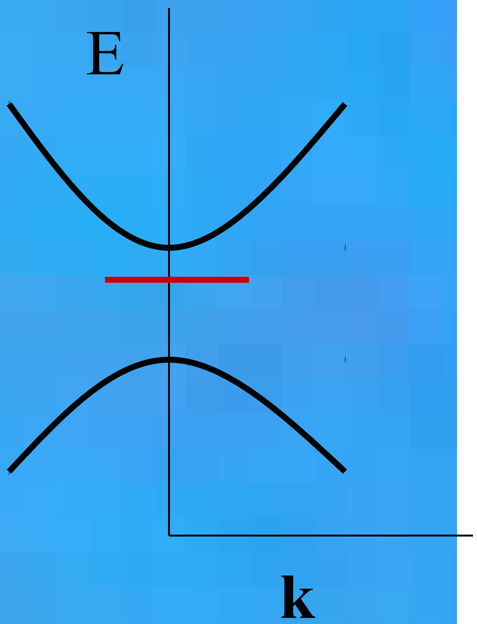
15% detection efficiency
>35% collection efficiency

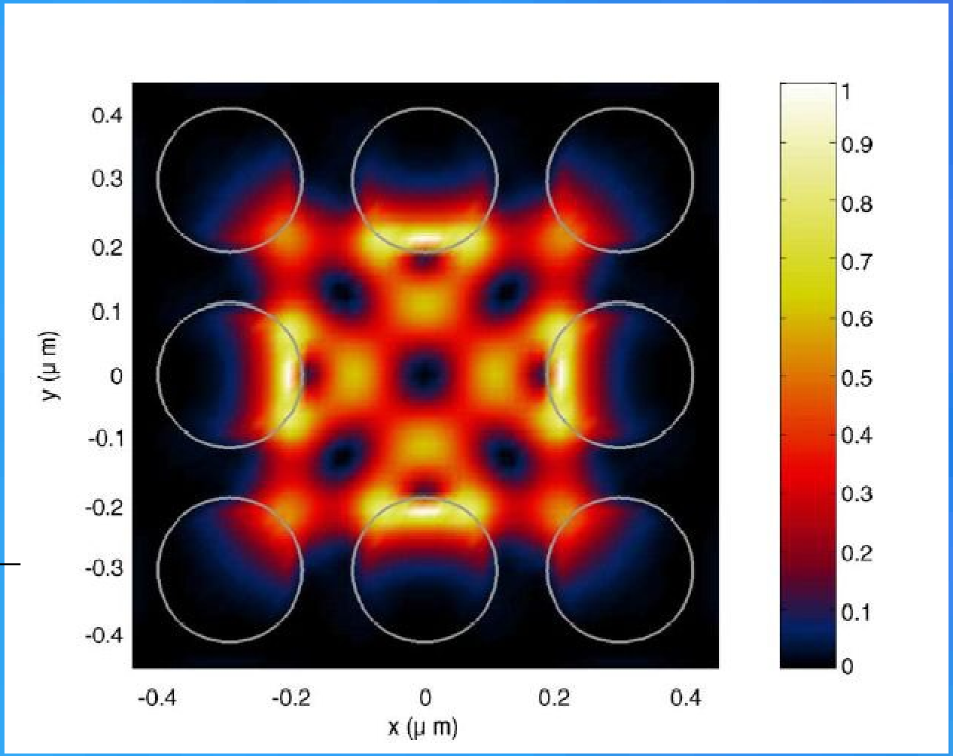
fs probe	cw probe
3.6/24 MHz	**12/80 MHz**

Mode splitting



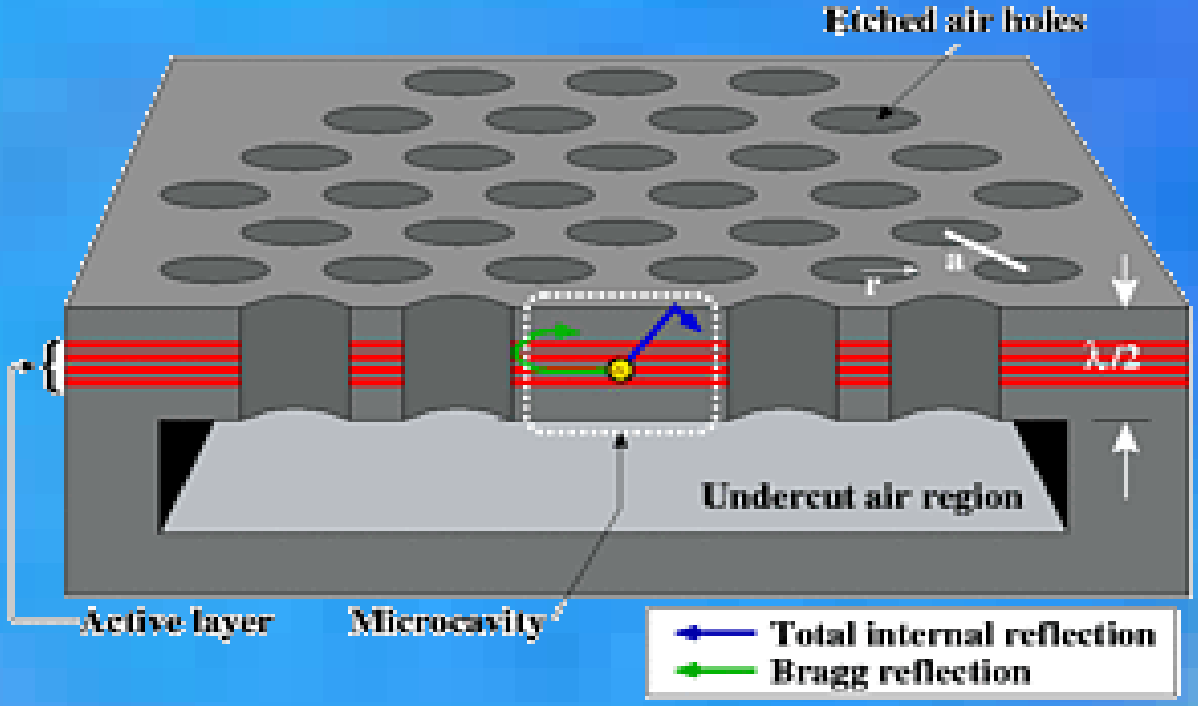






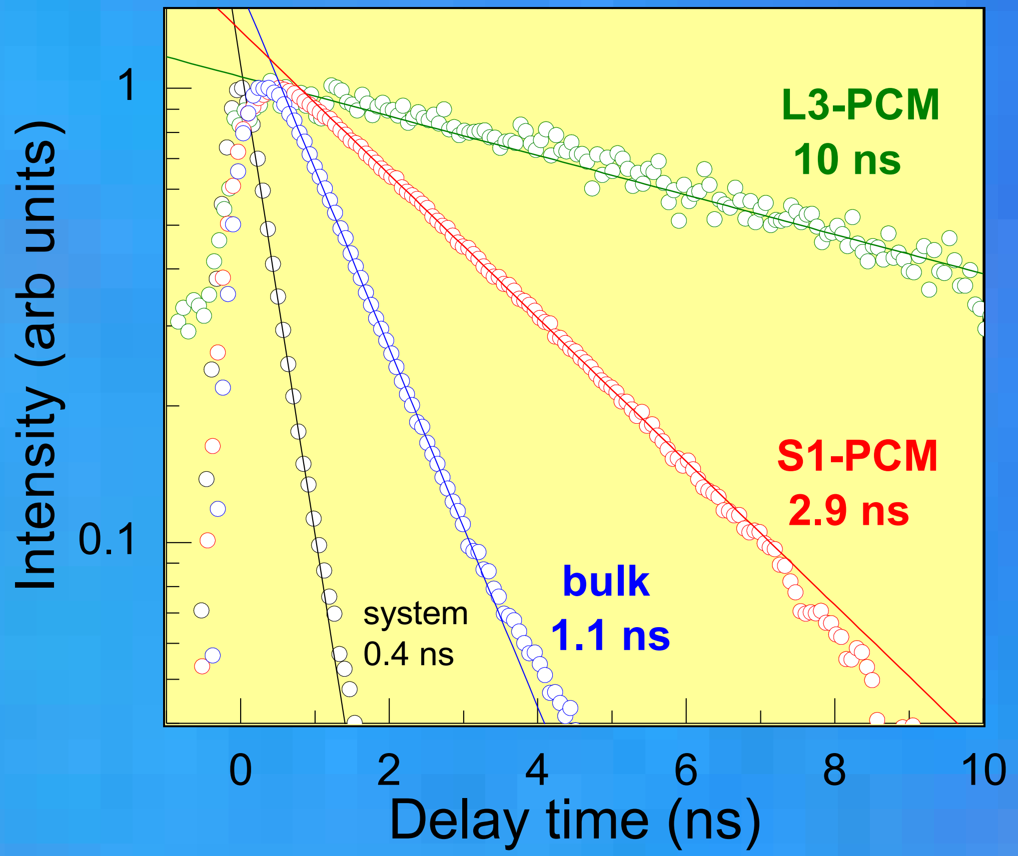
Very small mode volume:
strong coupling between EM field and embedded structures

2D photonic crystal membrane cavities



Inhibition of single QD emission

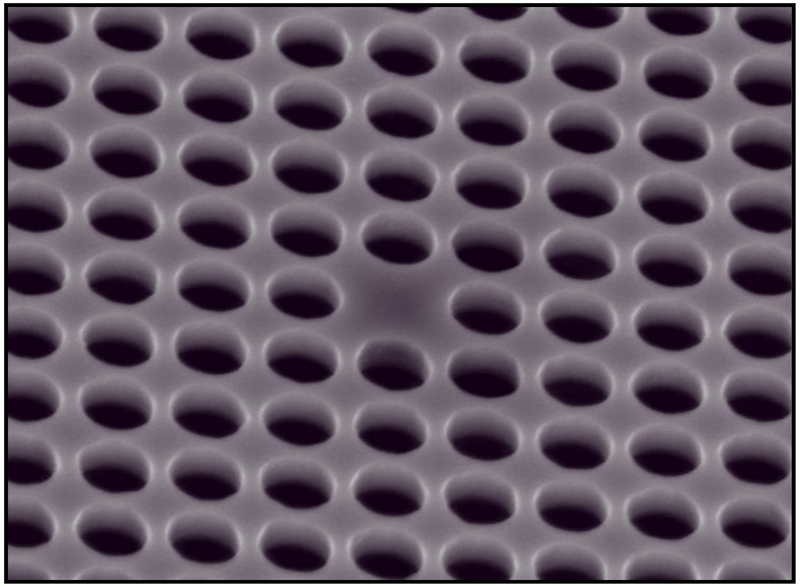
Single QD lifetimes



10x inhibition of SE

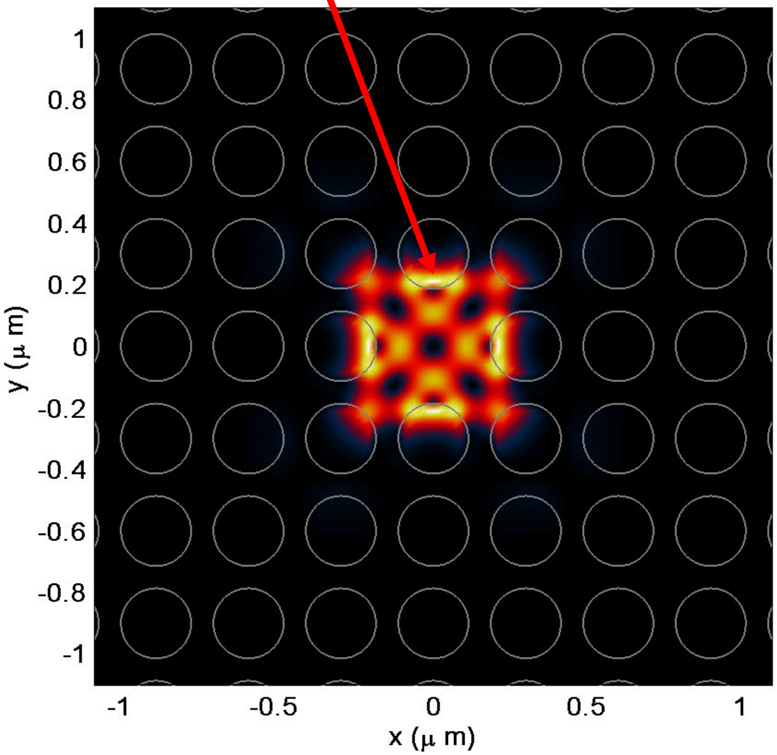
Photonic crystal cavity design I

Square lattice (S1)



Q~5000

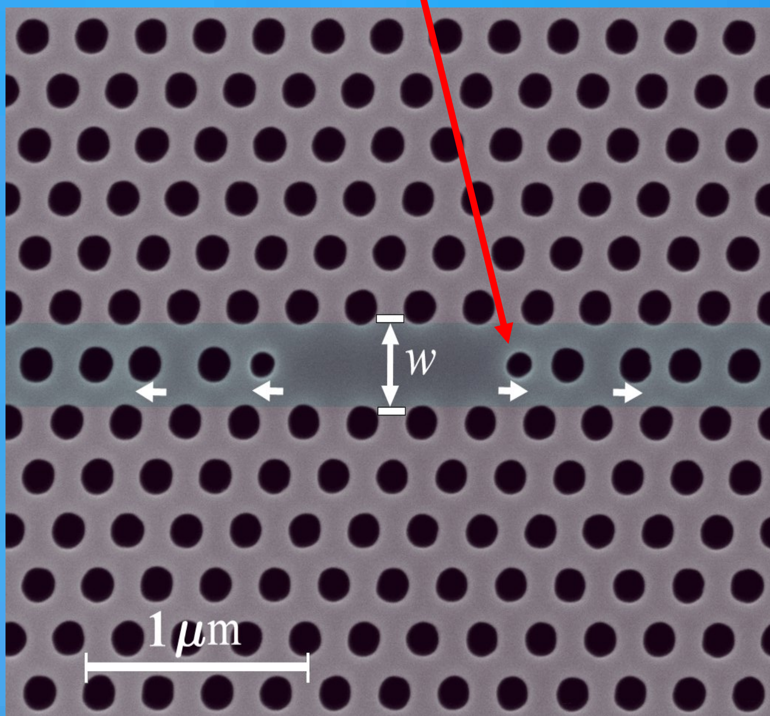
Mode localized at semiconductor/air interface



"Random QD positioning"
Poor QD properties at interface

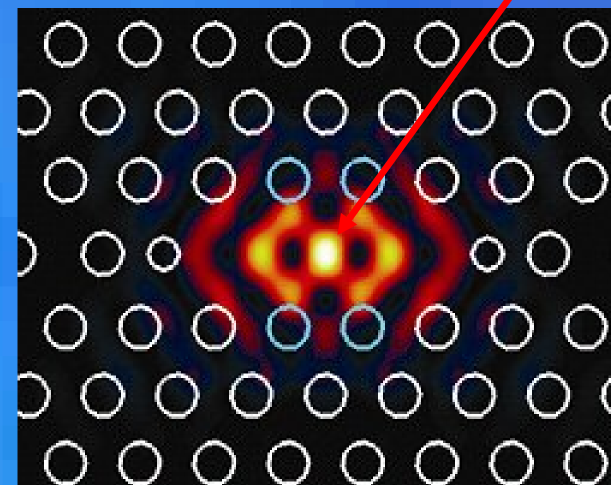
Photonic crystal cavity design II

Size and position optimized for high **Q** and high $\mathbf{n_{eff}}$



Field stays away from interface

Top View



Side View

Mode volume	**V ~ 0.68(λ/n)³**
Effective index	$\mathbf{n_{eff}}$ **~ 2.9**
Q-factor (in theory)	**> 200000**

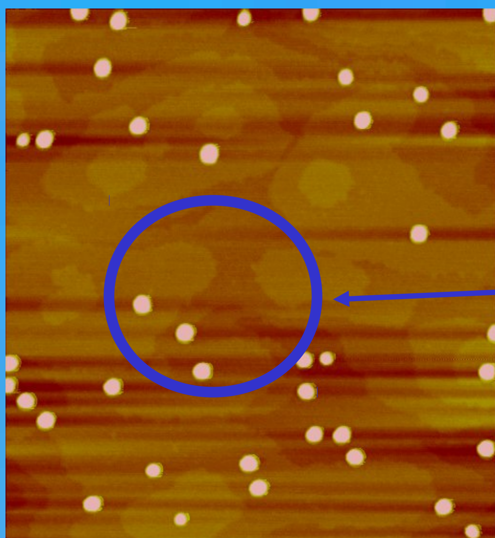
Measured Q ~ **18000**

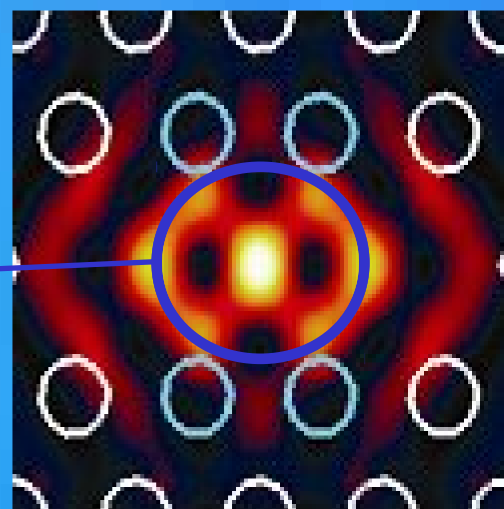
GaAs !

Low density of QDs

QD density
5-50 μm^{-2}
from AFM

Mode volume
from FDTD





QDs are spectrally distributed over 50-100 nm

Sharp exciton resonance

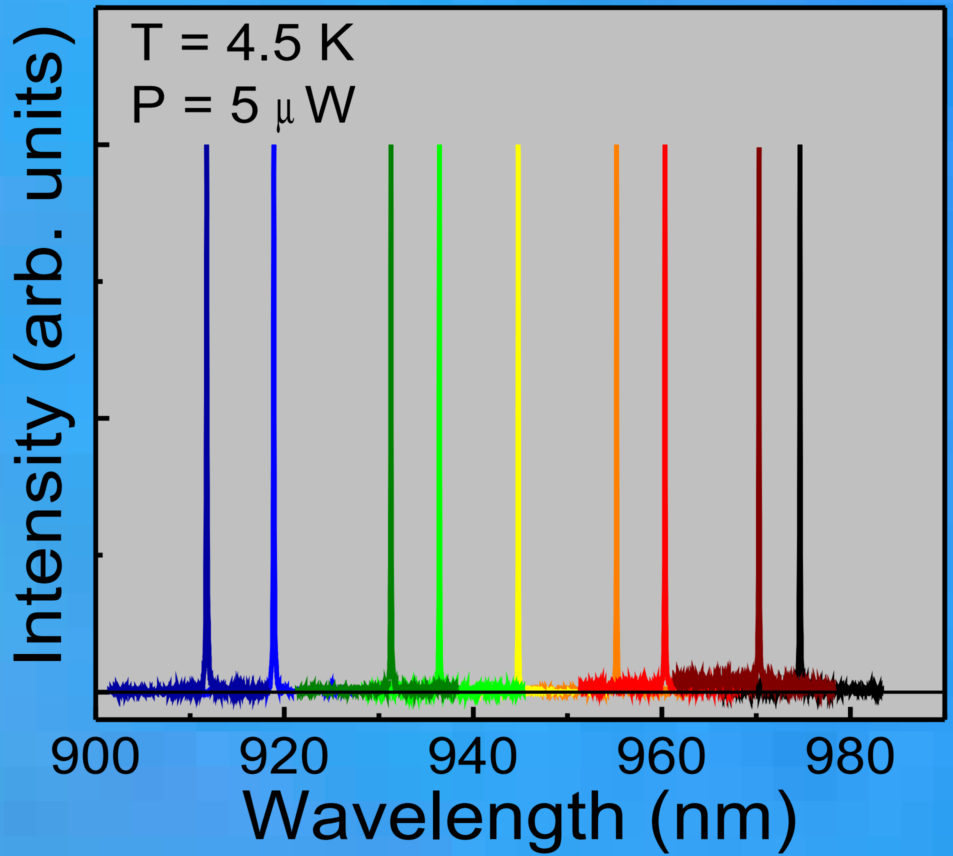
Chance of **~ 1%** for both spatial and spectral coupling

Only **1-3 QDs** are within the mode !

No pronounced coupling is expected

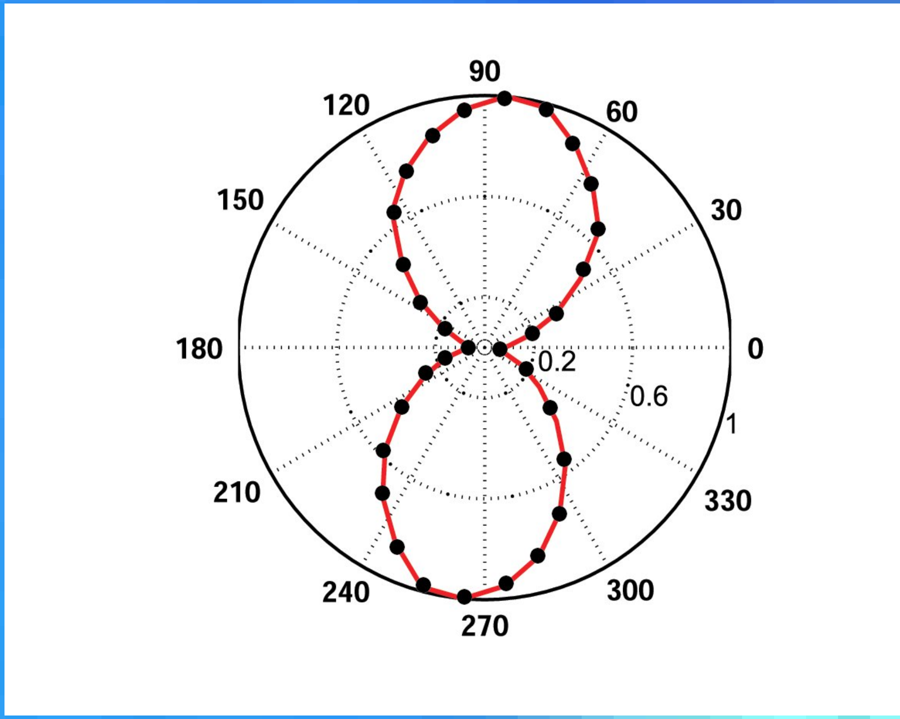
Lasing!?!?

Single mode lasing spectra



No QDs – no mode decoration

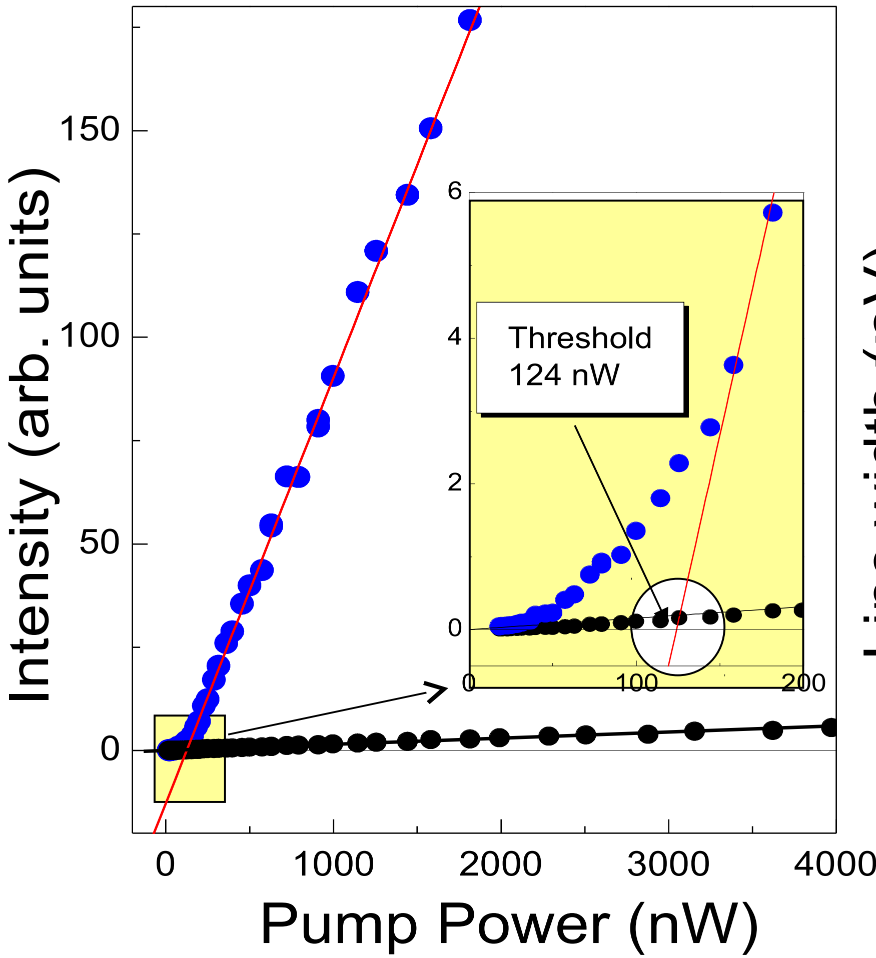
Nondegenerate lasing mode



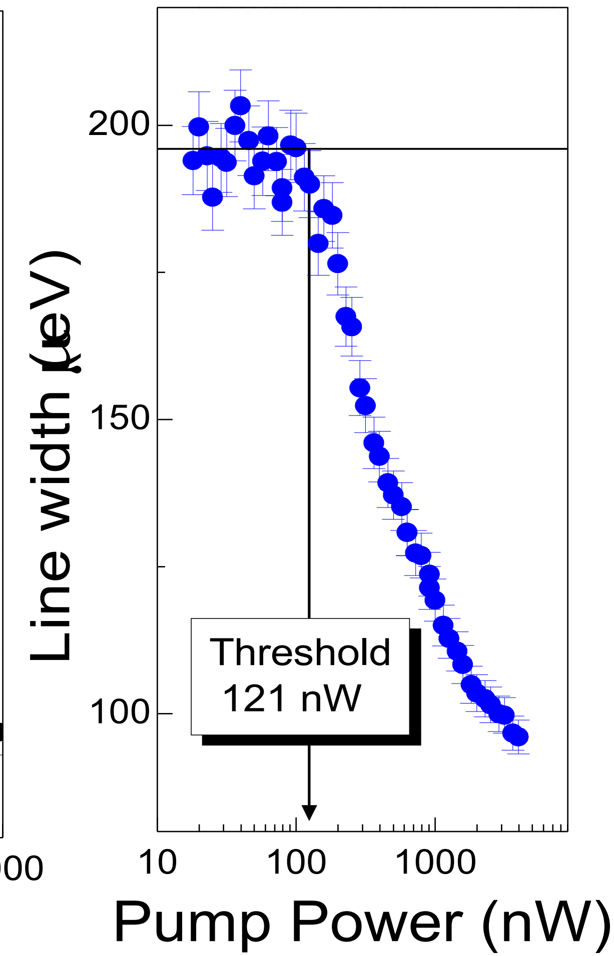
β~1 expected

Lasing threshold behavior

Vanishing-threshold



Linewidth narrowing

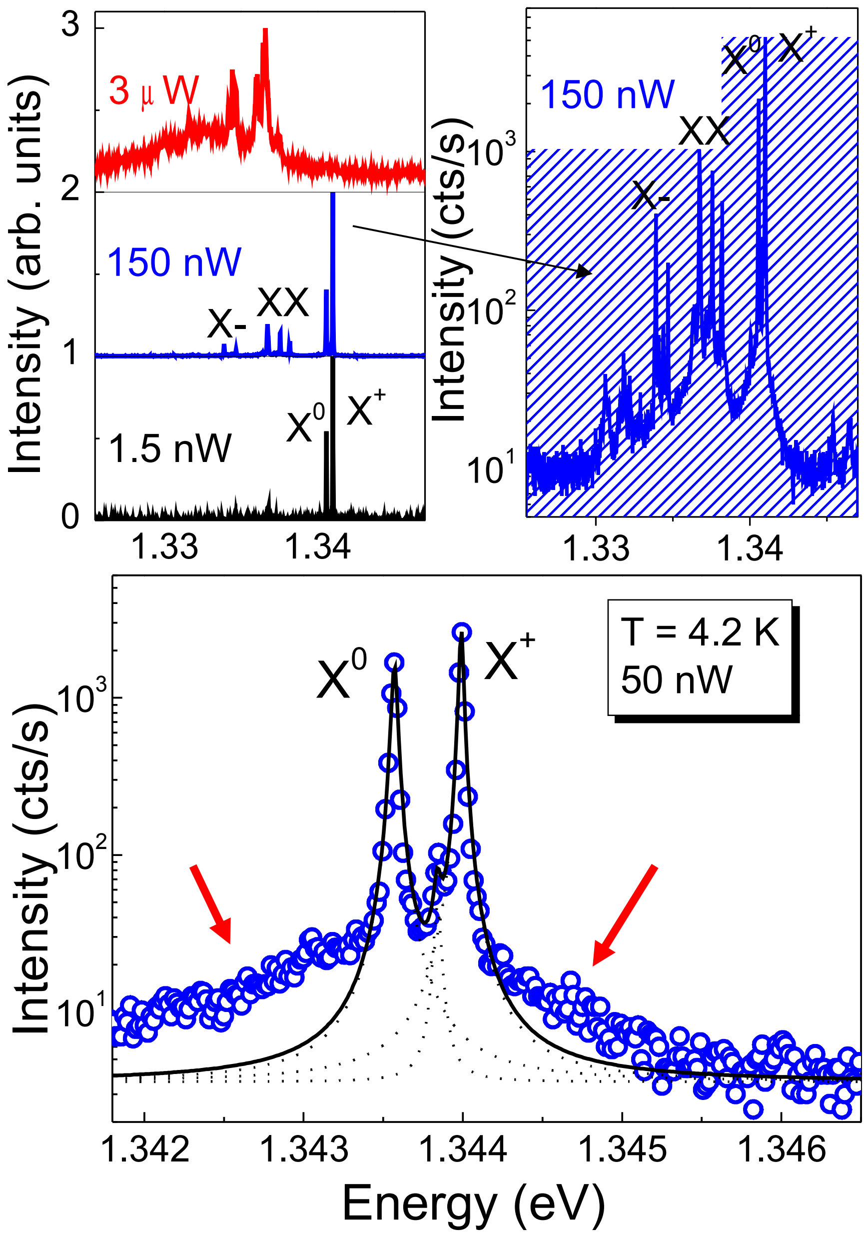


Conventional cw-threshold:
~100 nW

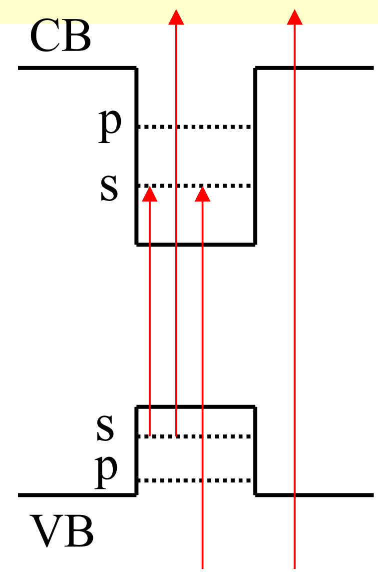
Absorbed power:
~4 nW

~ 10^2 -10^3 times lower than previous reports

Single QDs are broadband emitters



- charged states X^+, X^0, X^-
- bi- and multi Xs
- Extended state



- acoustic phonon coupling

QD interaction with surrounding matrix provides **indirect** but **robust** coupling

Single QDs are broadband emitters