Nanoscale single quantum dot devices at 1300 nm

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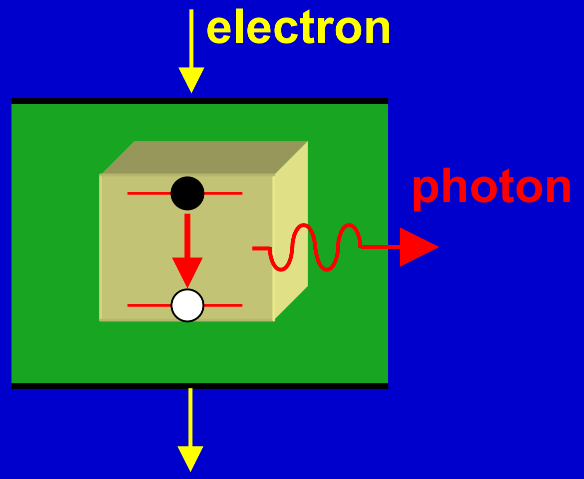
Funding: Swiss National Science Foundation

Outline



- Single-photon emitters
- Practical issues for single-photon emitters:
  - Wavelength & density: Growth of QDs at 1300 nm
  - Electrical injection: Nanosized QD LEDs
  - Controlling the optical density of states
- Conclusions

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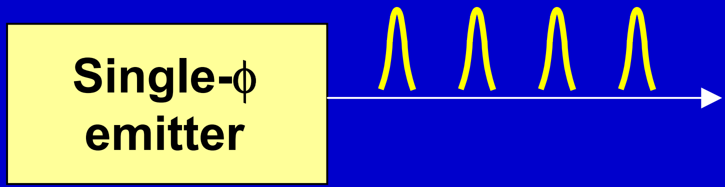
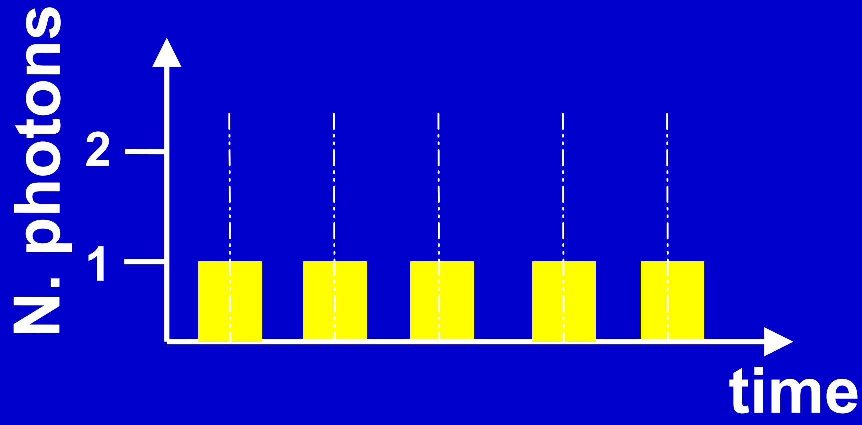
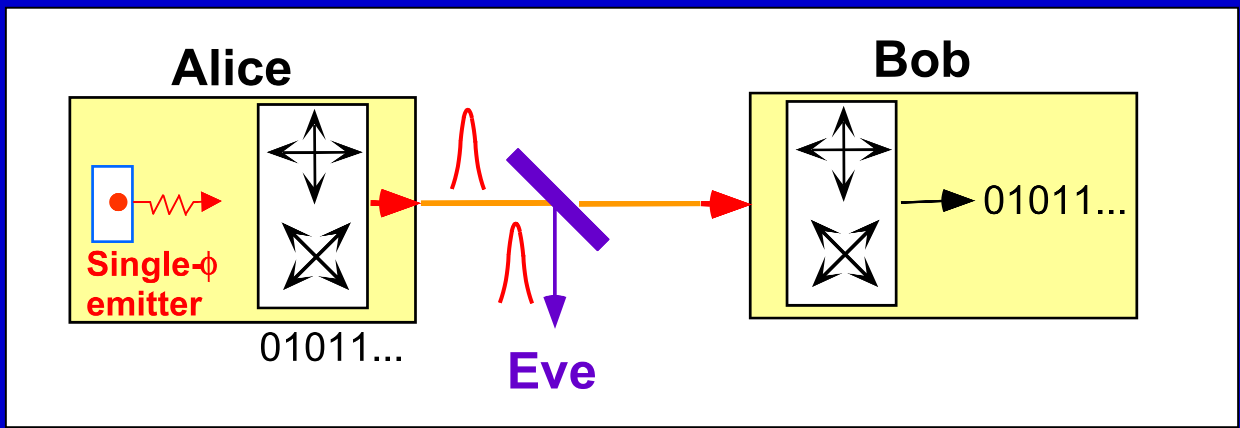
Single photon emitters





Application: Quantum cryptography



BB84 quantum key distribution

id Quantique
A quantum leap for cryptography

MagiQ

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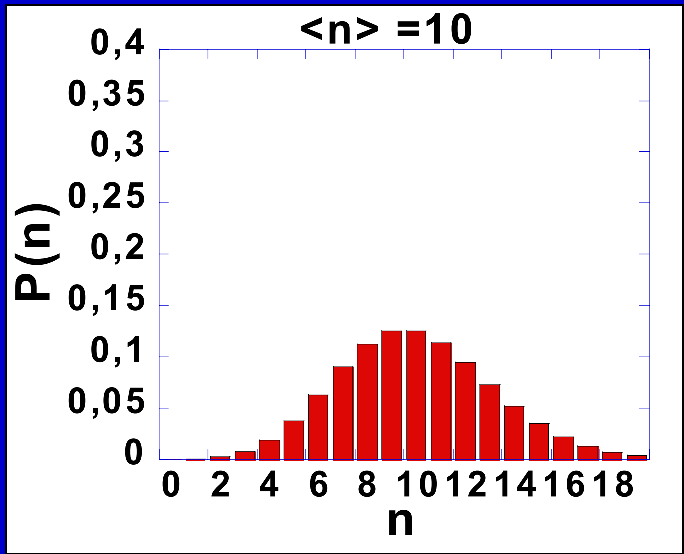
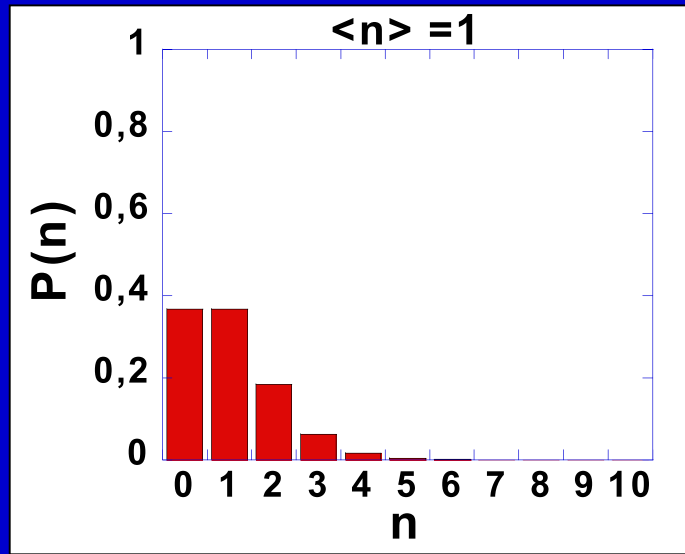
A close look at single photons

"Classical" light sources (e.g. a laser) are Poissonian:

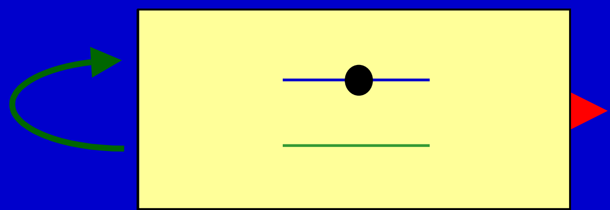
$$\sigma_n^2 = \langle n \rangle$$

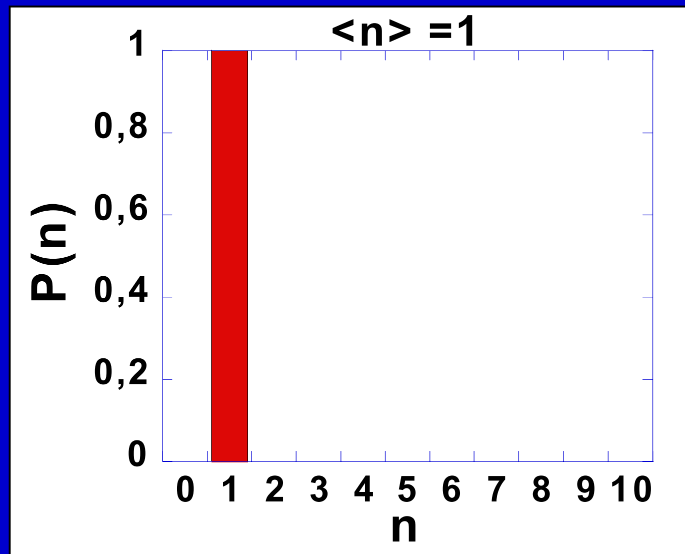




"Nonclassical" light source:

Single quantum system:





The quest for single-φ sources

The simplest single-φ sources:

- Single atoms
- Single ions
- Single molecules
- ...

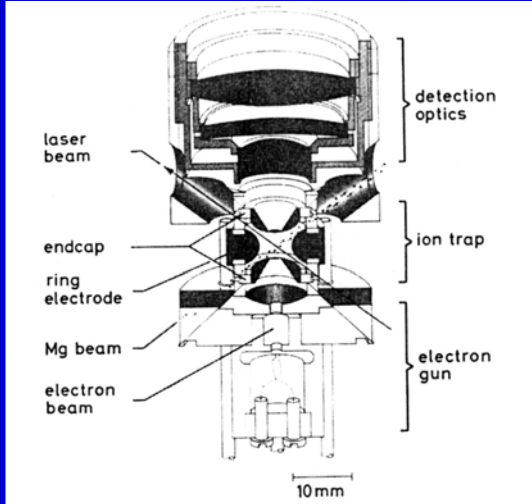
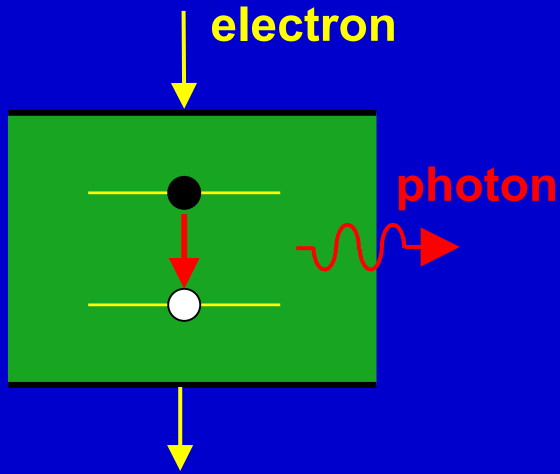


FIG. 1. Radio-frequency trap. The fluorescence light of the stored ion is observed through a bore in the upper pole cap.

(Diedrich and Walther, PRL 1987)

Wish list **for single-φ sources:**

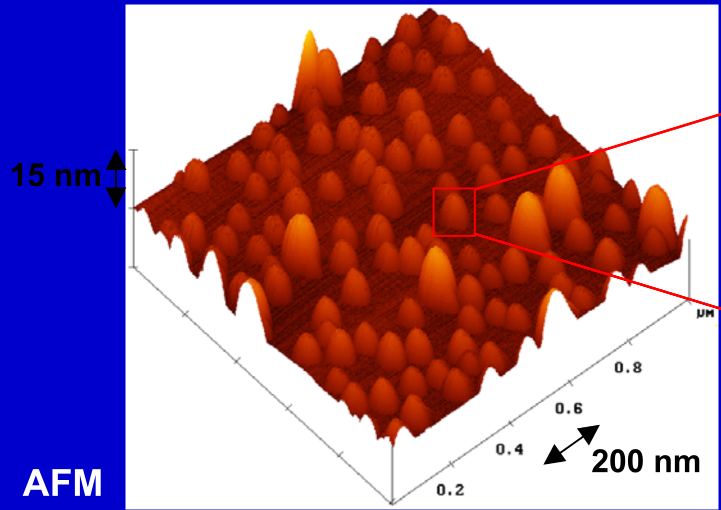
- Compact, electrically pumped
- Efficient
- Emitting at 1300-1550 nm

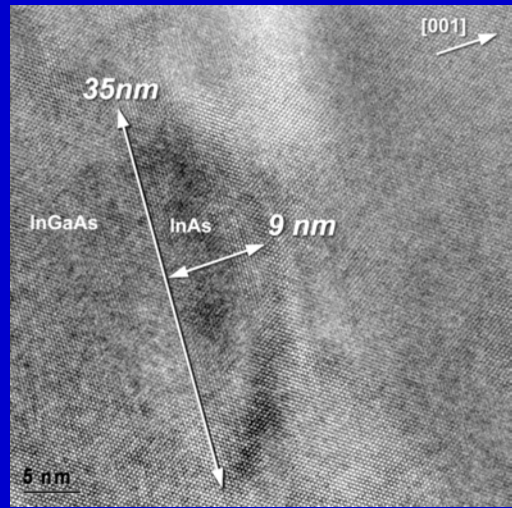


⇒ A semiconductor LED!

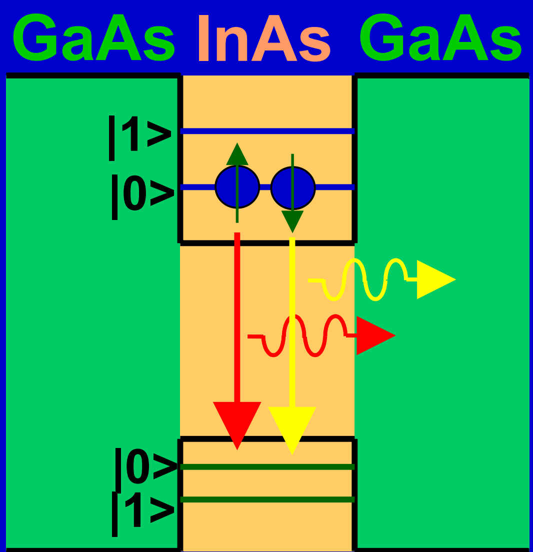
Semiconductor Quantum Dots

MBE growth of InAs on GaAs:

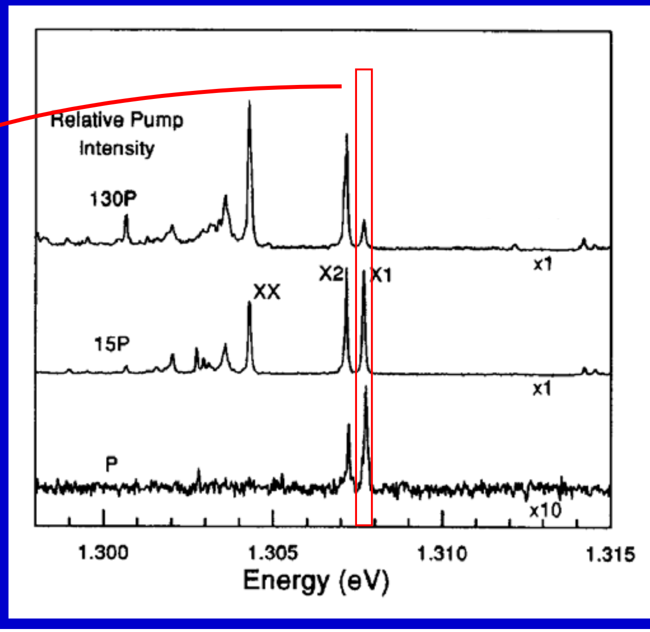




TEM

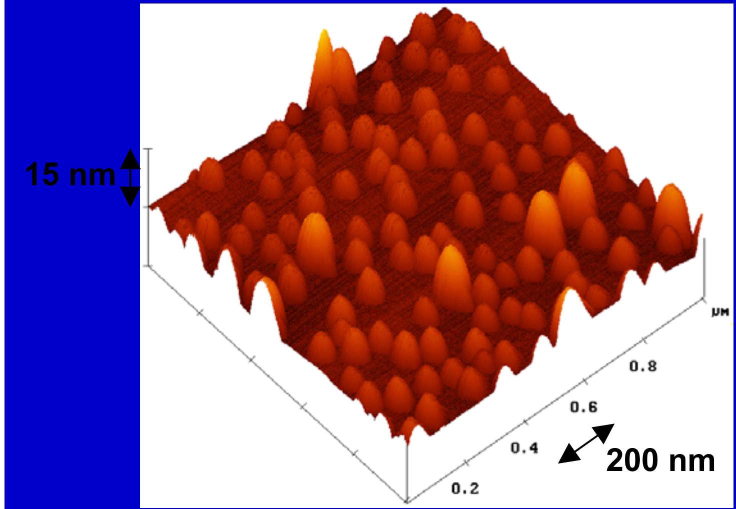


Single-photon emission



(Kiraz et al., PRB 2002)

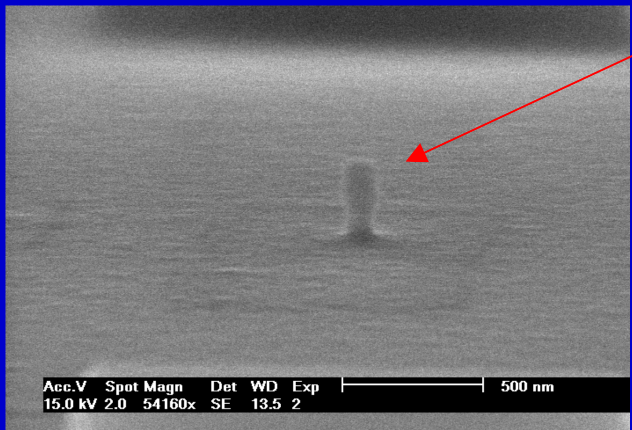
Isolating single QDs



High areal density

Need very high spatial resolution!

Nanomesas:

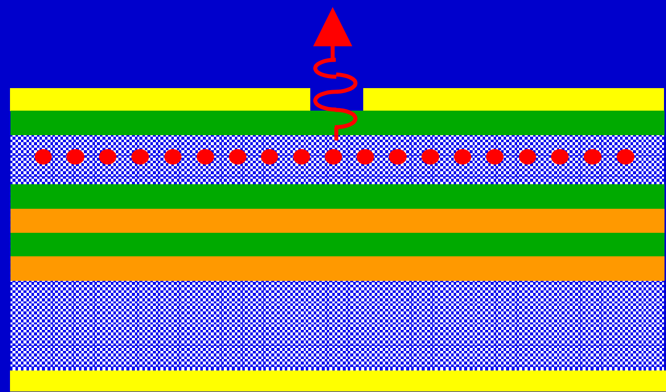


≈ 100 nm

≈ 1 QD

CNR-IFN Roma

Shadow-mask apertures:



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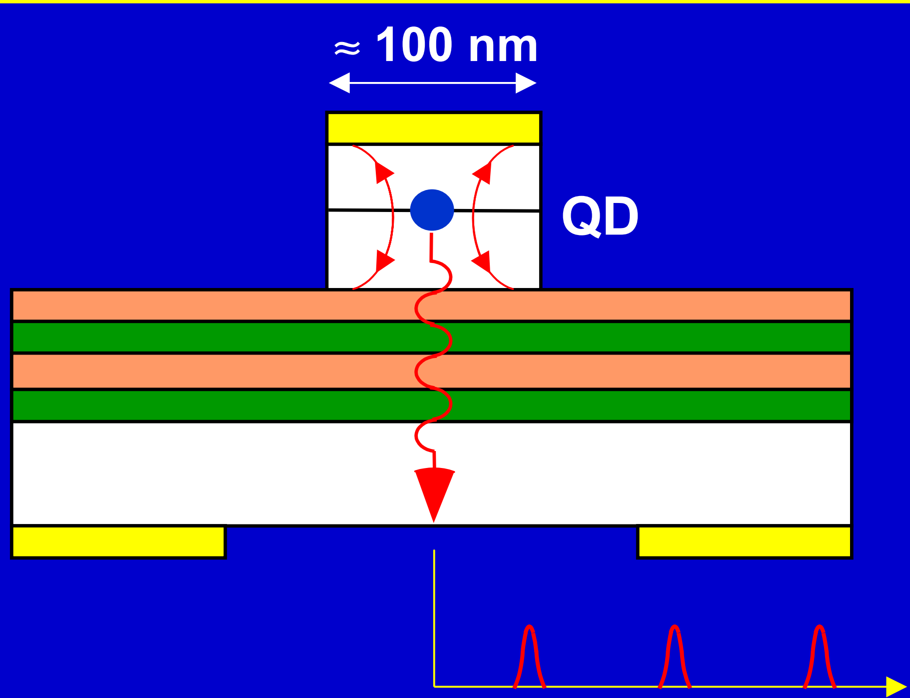
Towards practical single-ϕ emitters

Single-QD LED ?

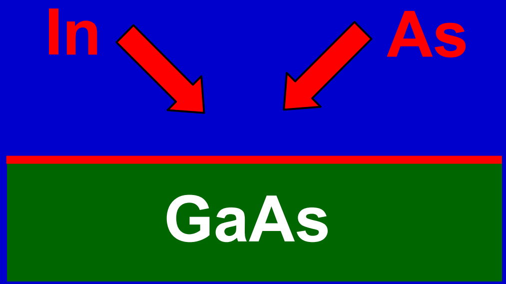
- Electrical pumping ?
- Efficiency ?
- Emission at 1300 nm ?

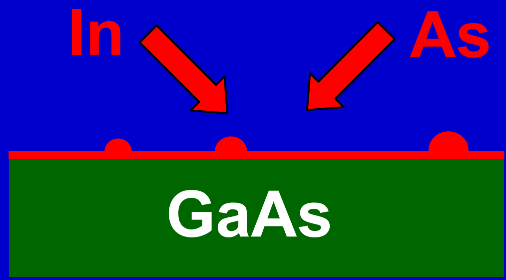


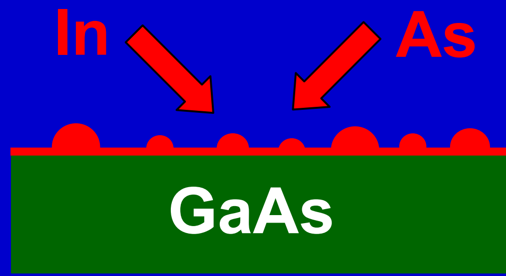
Our approach:

- Sparse InAs/GaAs QDs at 1300 nm
- Nanostructured LEDs
- Nanocavities for efficient LEDs

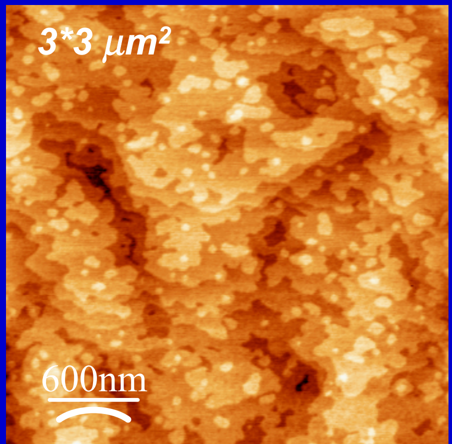
Controlling the density by the coverage



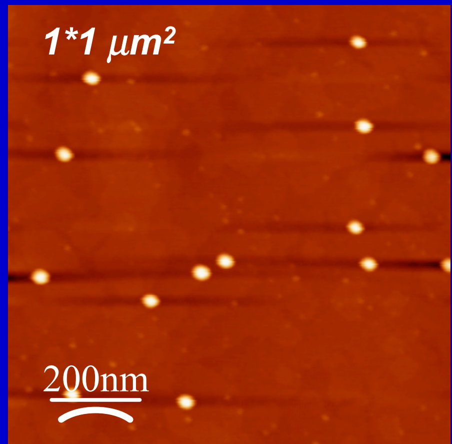




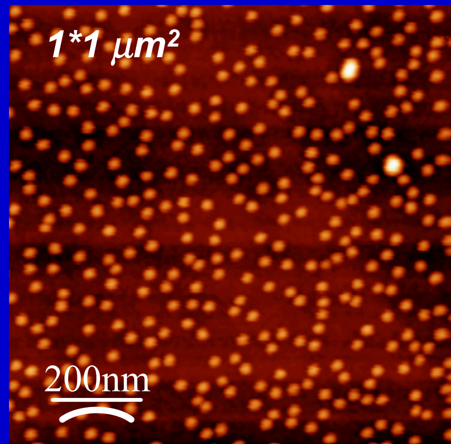
530°C, 0.163 µm/hour:



1.7 MLs< critical thickness
No QDs, streaky RHEED



1.8 MLs ≈ critical thickness
15 µm^{-2}, slightly spotty RHEED



3 MLs>> critical thickness
340 µm^{-2}, spotty RHEED

- **Low density at low coverage** ***(Leonard et al., PRB 1994)***
- **Wavelength?**

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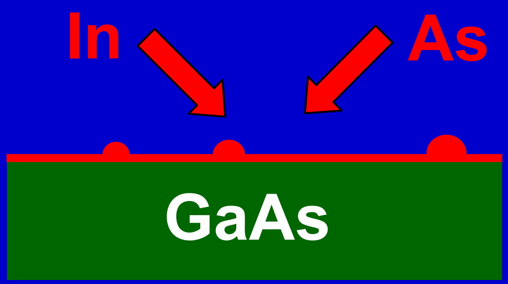
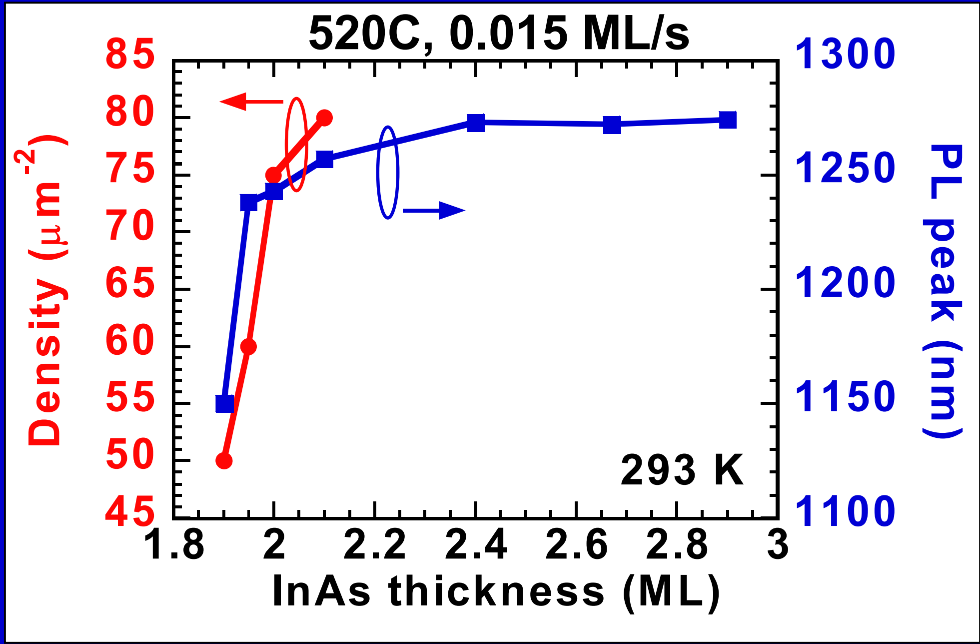
Low-density QDs

Coverage affects emission wavelength:



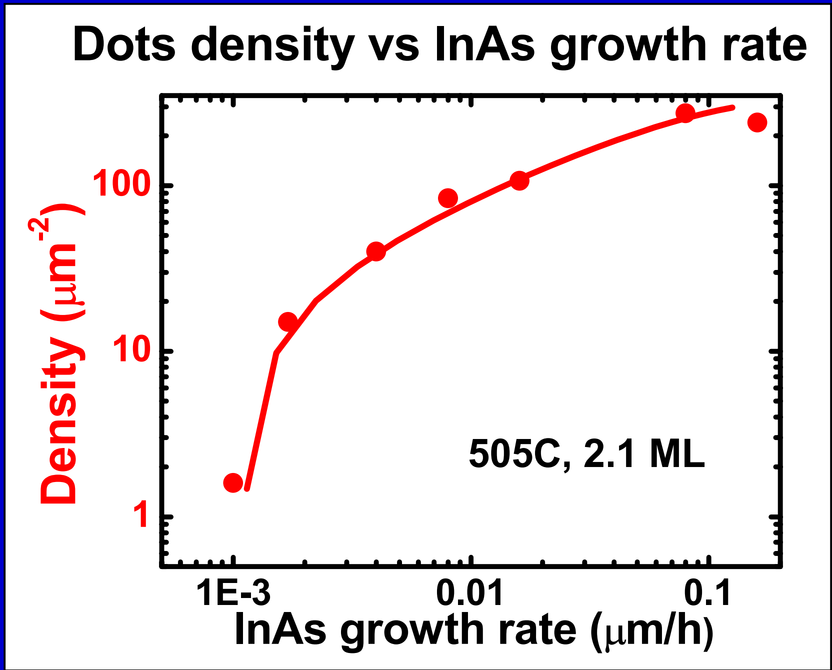
Blue-shift at low coverage (smaller QD size, lower In content)

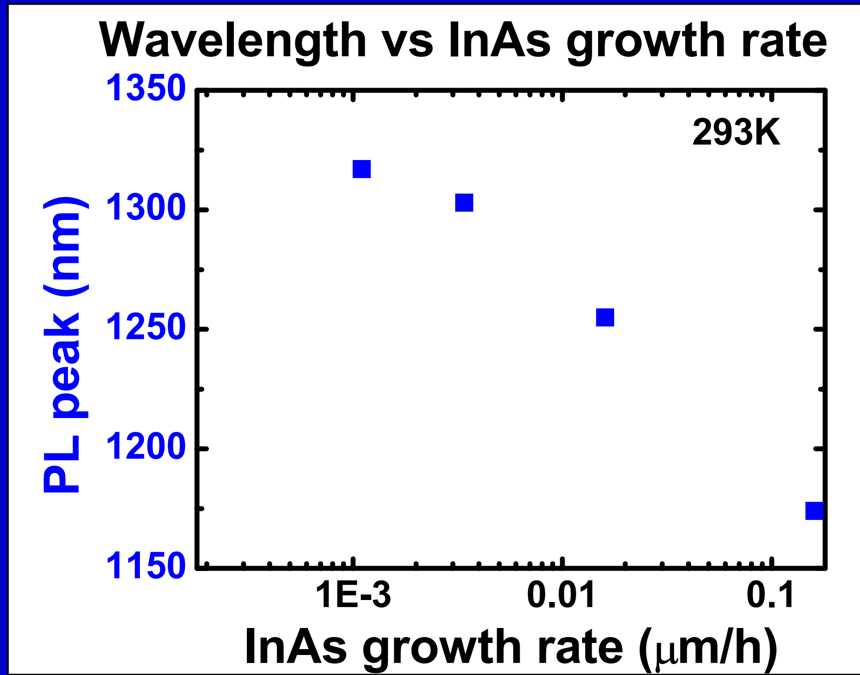


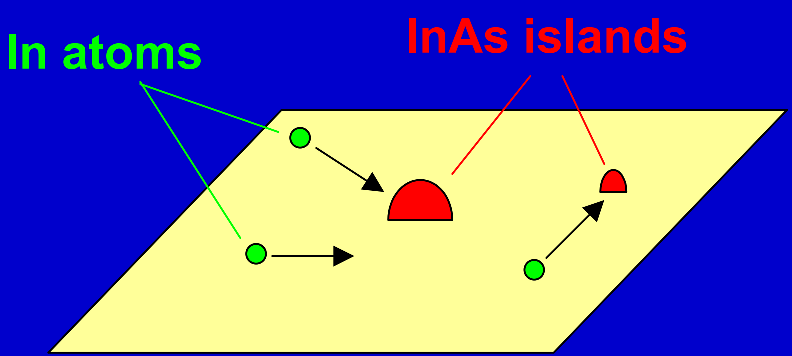
Difficult to grow large and In-rich QDs at small In coverage

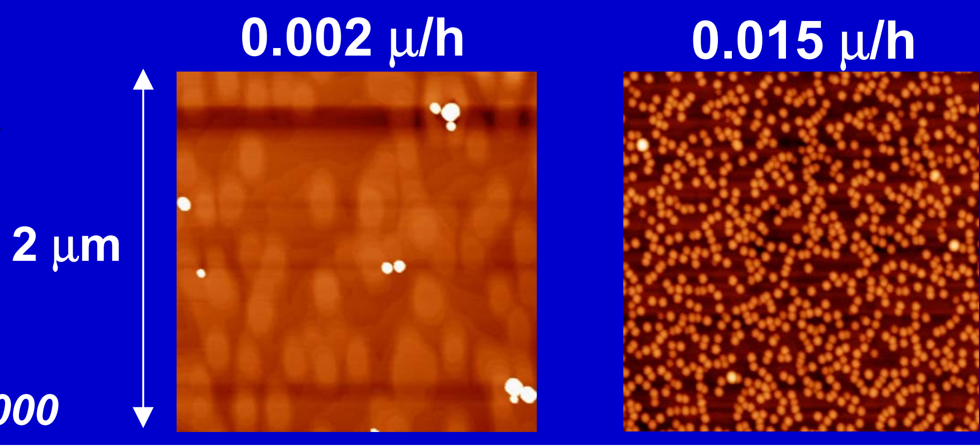
Growing *slowly*

Low growth rate ⇒ Increased diffusion length ⇒ Low density



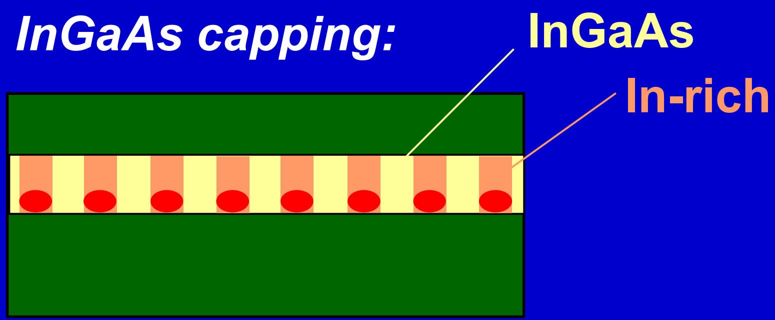




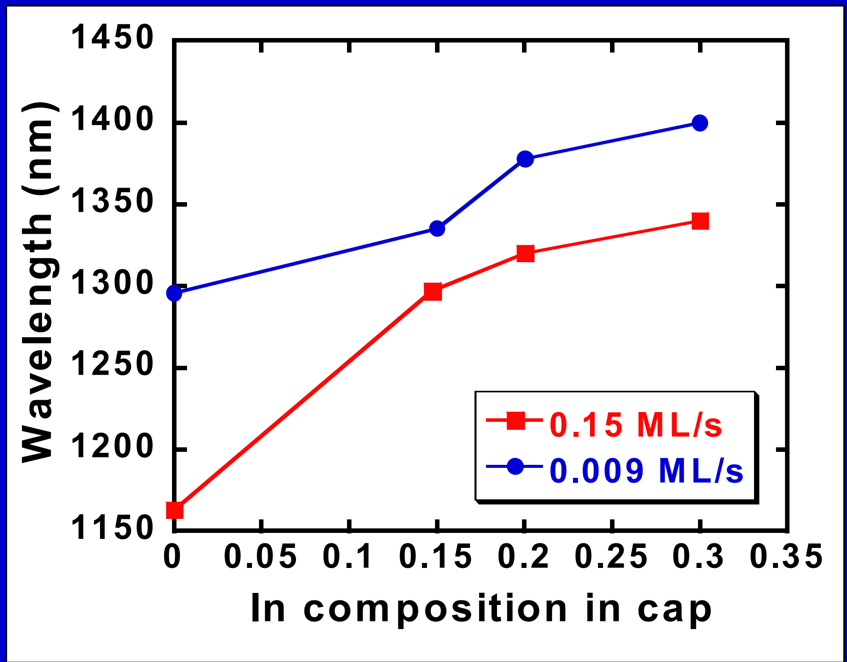


Joyce et al. PRB 2000, Nakata et al. JCG 2000

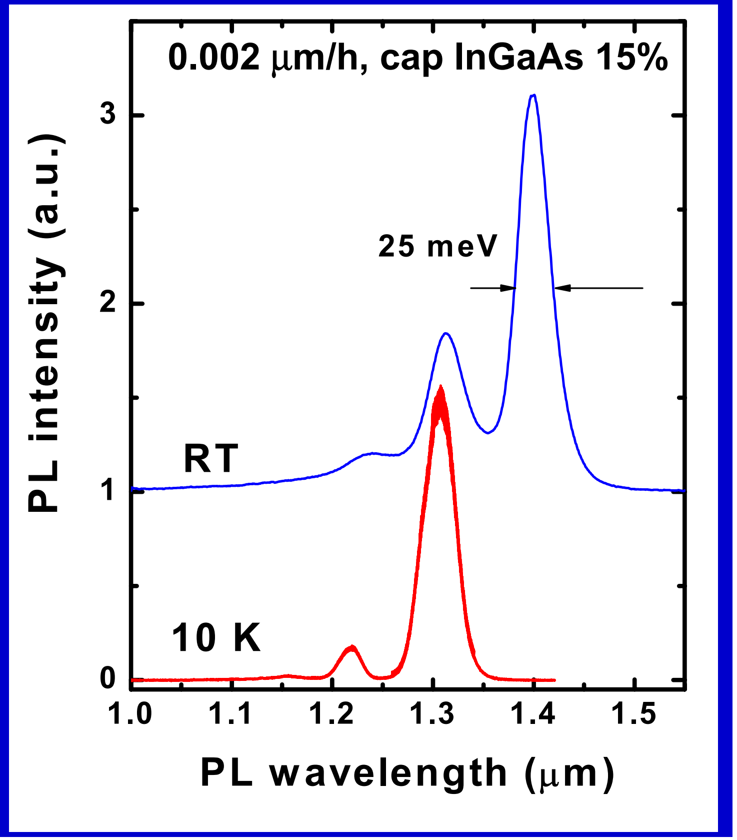
The role of capping



InGaAs capping:
- **Lower strain**
- **Reduced In segregation**

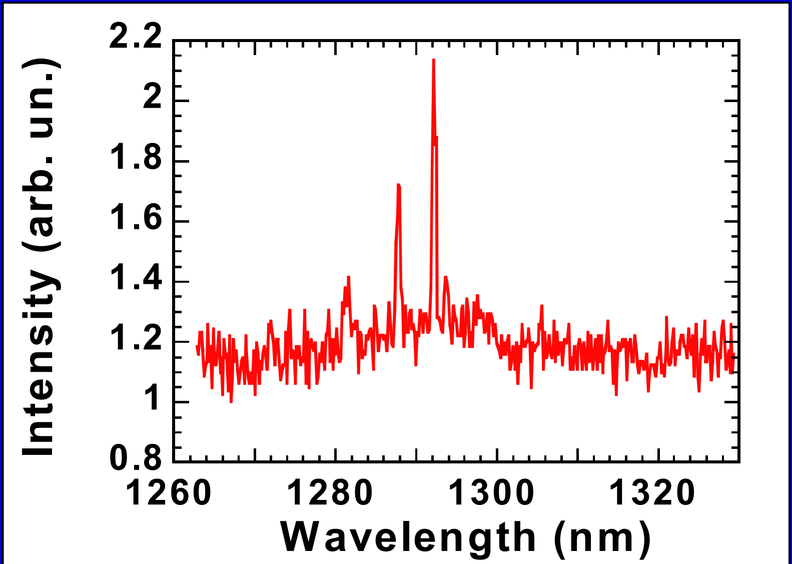


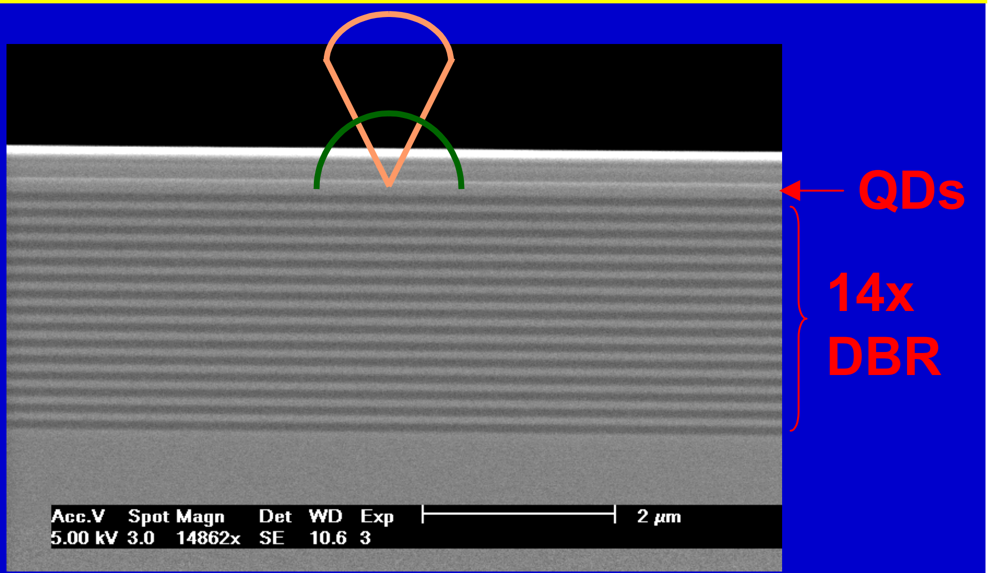
1300 nm at 5K:



Single QDs

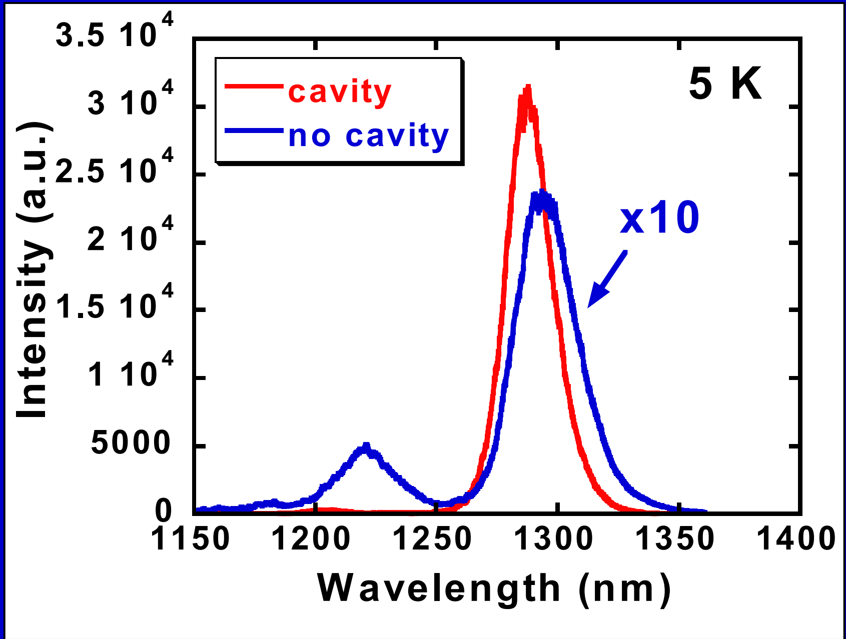
Single QDs in 2 μm-diameter mesa:



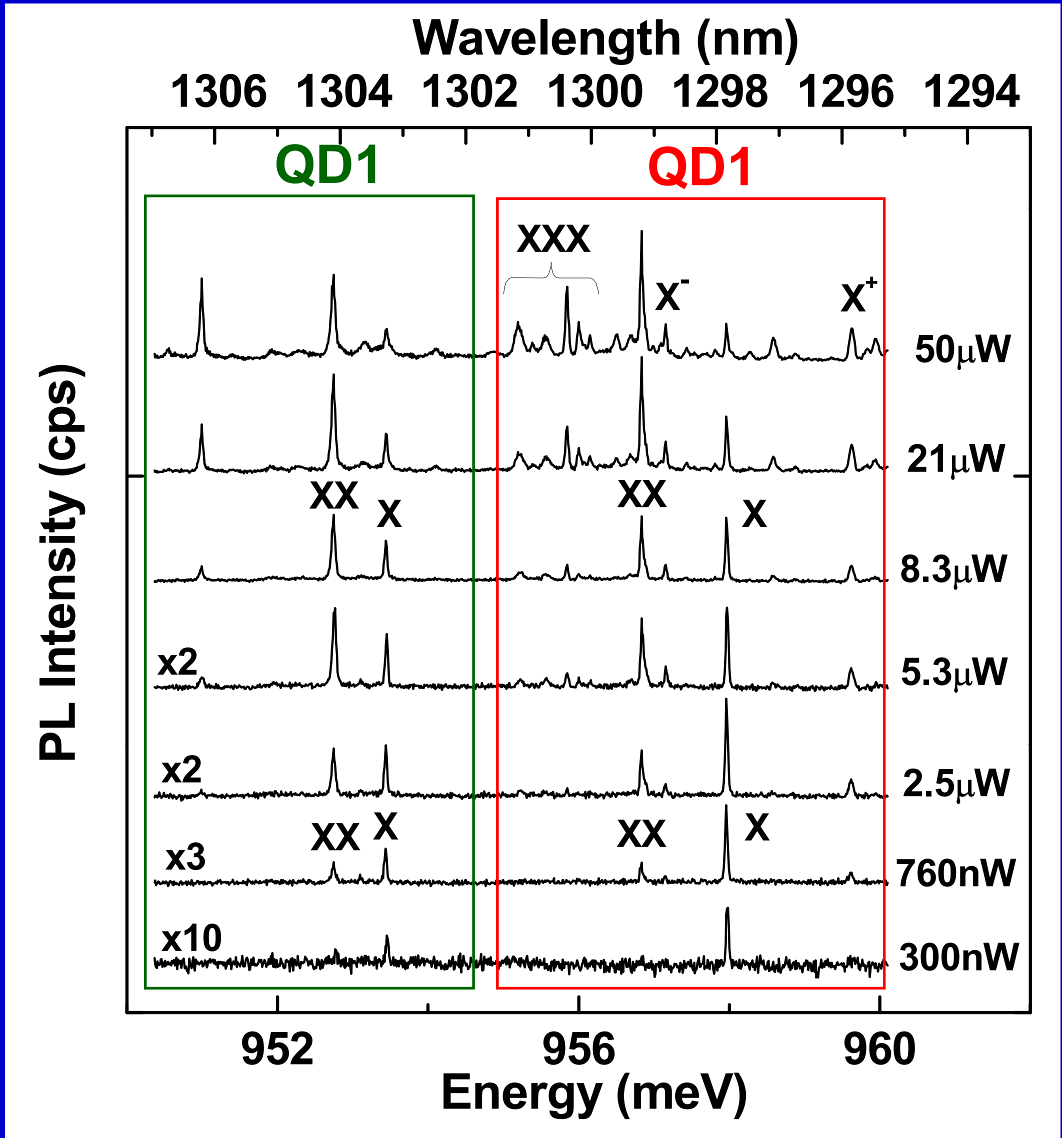


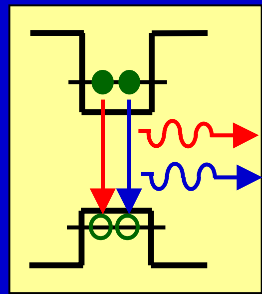
Low signal-to-noise due to noisy InGaAs detector

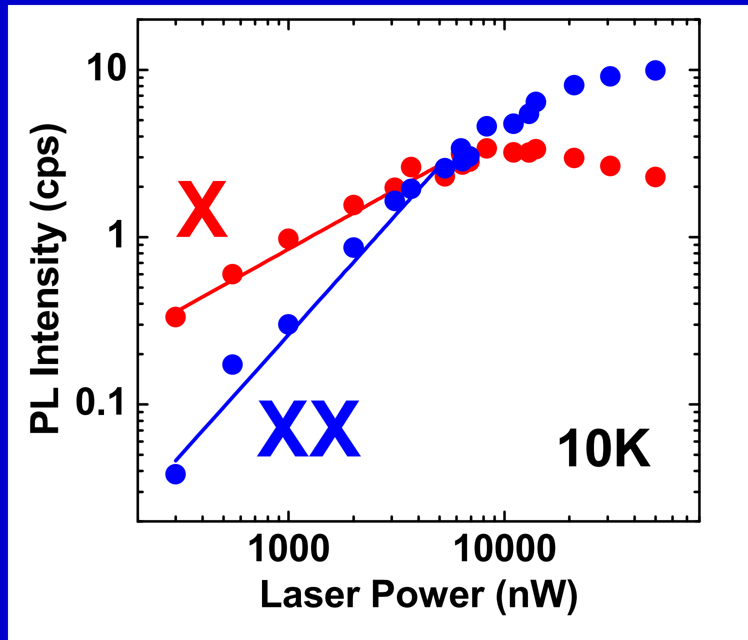
Increase light extraction with a microcavity



X-XX spectroscopy at 1300 nm



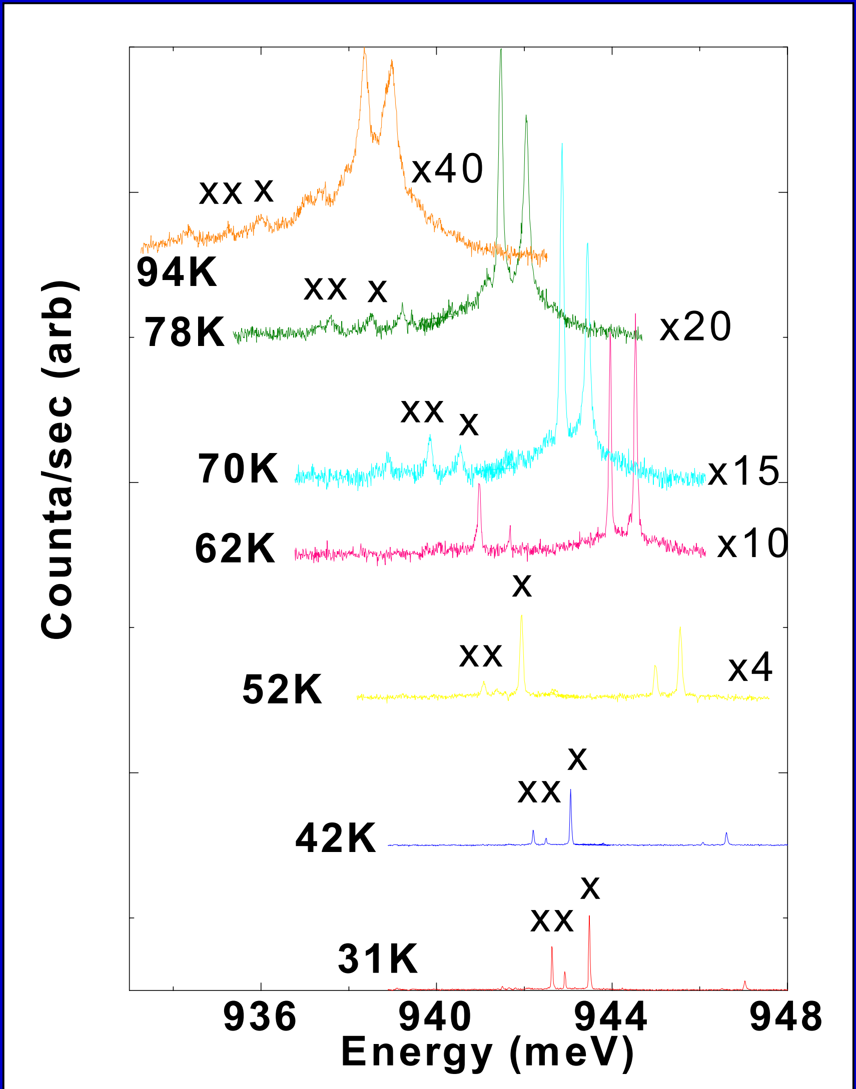




Alloing et al., APL, to be published

Temperature dependence

Single QD emission above 77 K:



- Population of charged exciton states at high T
- Homogeneous broadening of lines due to phonon scattering
- Single lines can be isolated up to T>77K

Towards LN_2-cooled single-photon sources at 1300 nm

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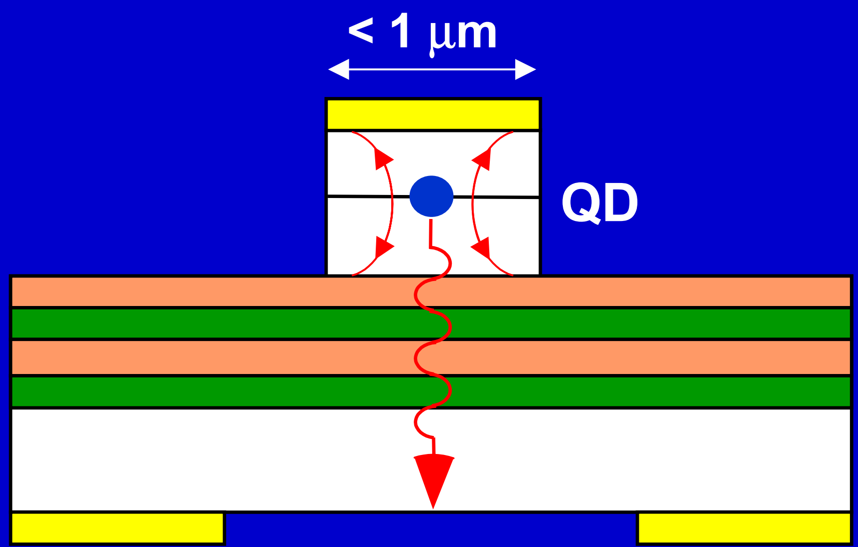
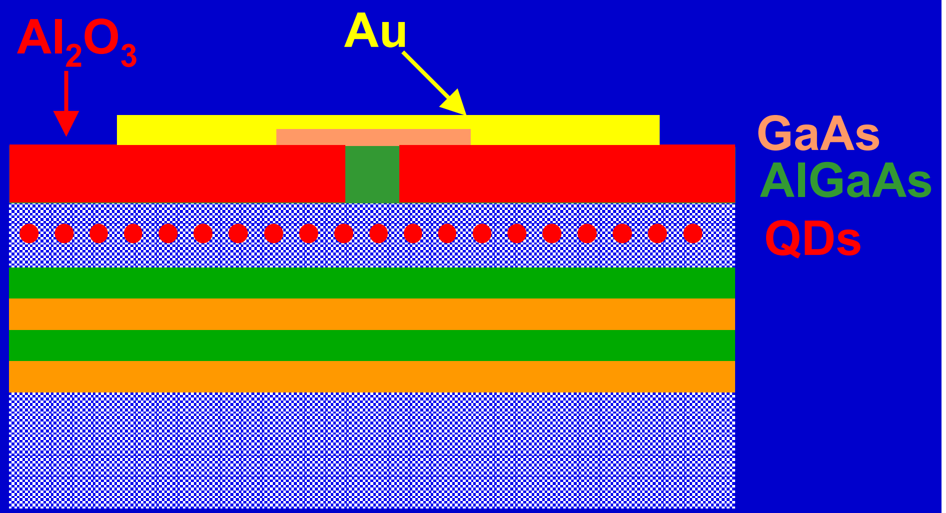
Fabrication of nano-LEDs





Etching:

☹ ***Defects ⇒ NR recombination***

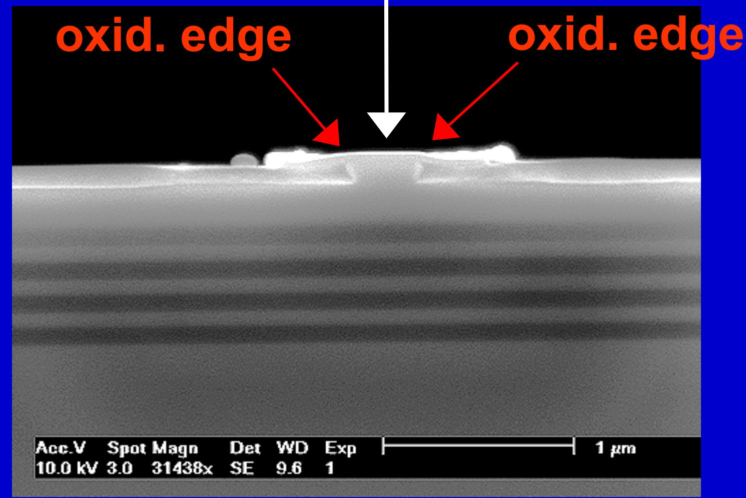
☹ ***Needs high-res. lithography***

Oxidation:

☺ **Does not create defects**

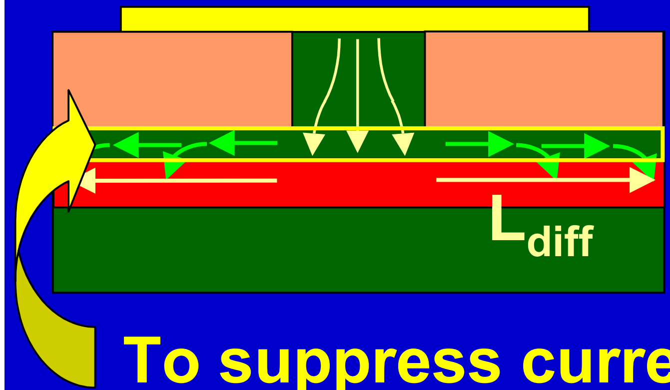
☺ **Smaller dimensions (<100 nm with optical lithography)**

300 nm current aperture



Fiore et al., APL 2002

Confining current injection



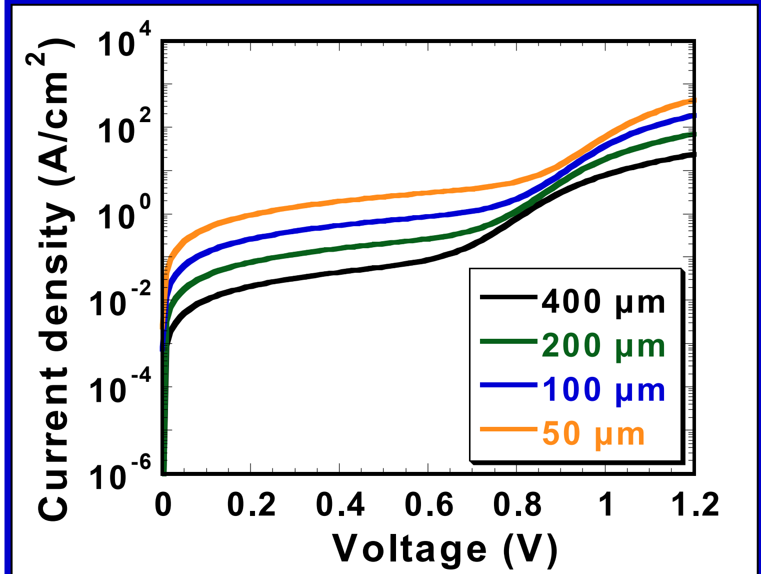
Current spreading: $L_{spread} = f\left(R_{//}, R_{\perp}\right)$

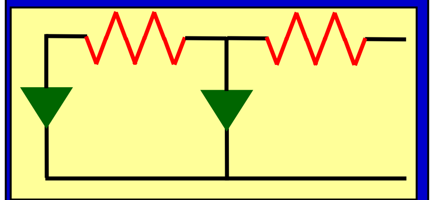
Carrier diffusion: $L_{diff} = f\left(\text{material}\right)$

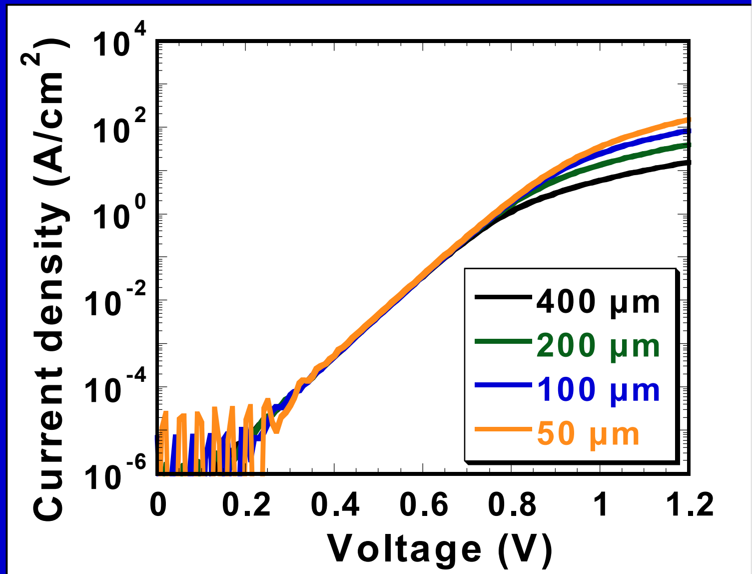
To suppress current spreading: Bandgap engineering of hole injector

doped p-injector:

undoped, graded p-injector:

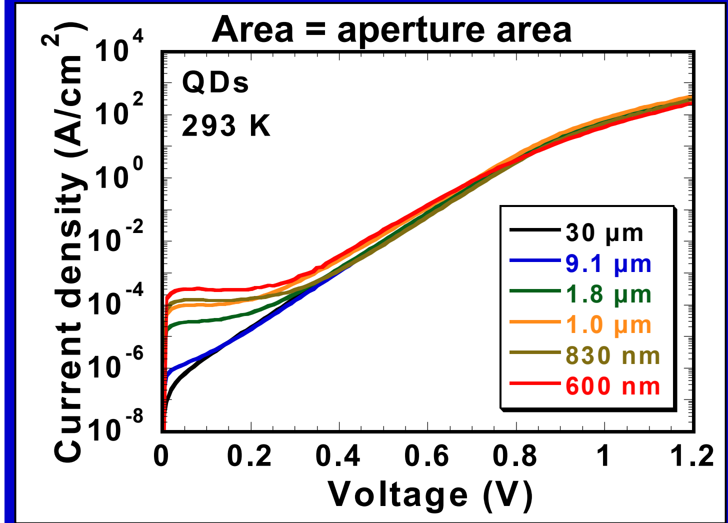


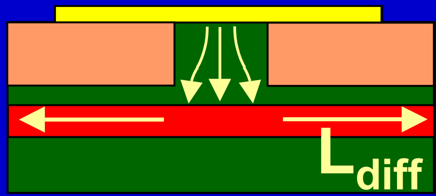




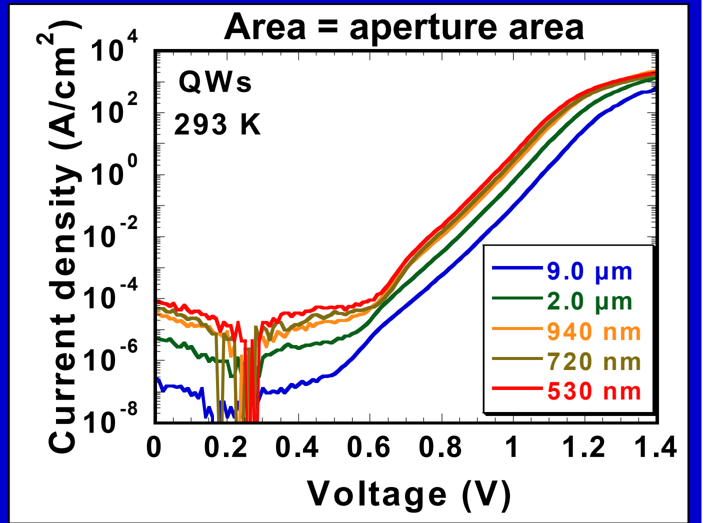
Ultrasmall LEDs: Scaling

Quantum dots:

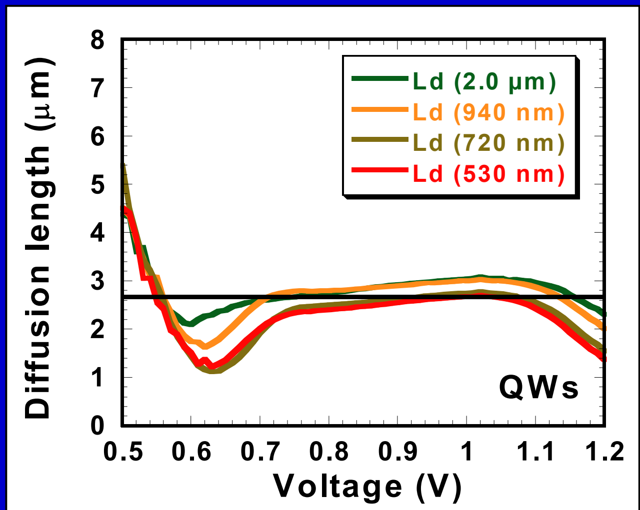


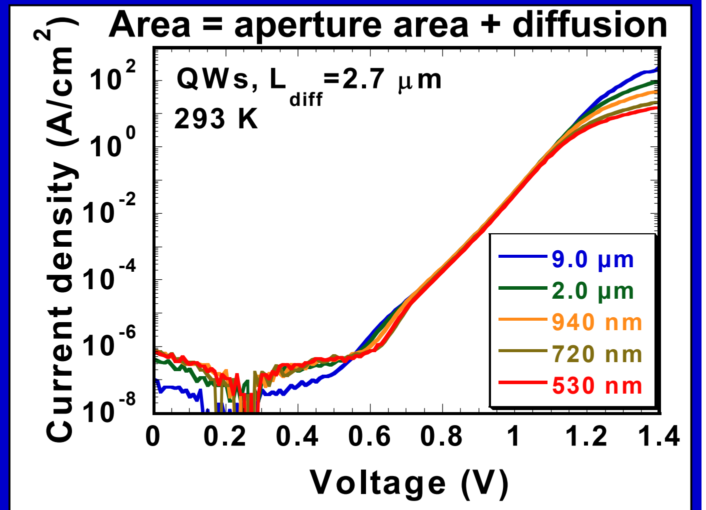


InGaAs quantum well:



Estimating diff. length from IVs:

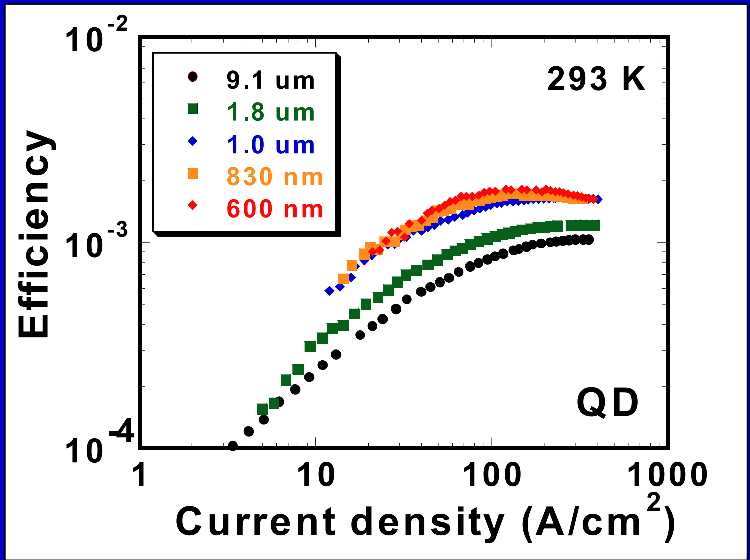




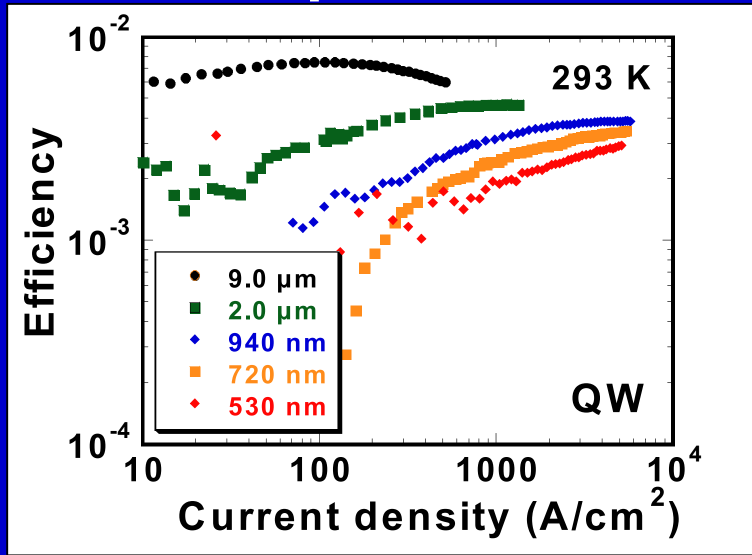
QWs: ≈ 2.7 µm
QDs: < 100 nm

Ultrasmall LEDs: Efficiency

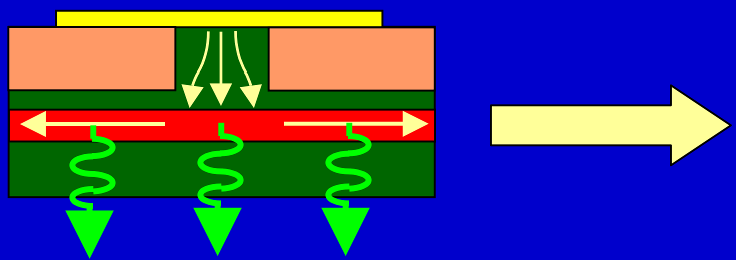
Quantum dots:

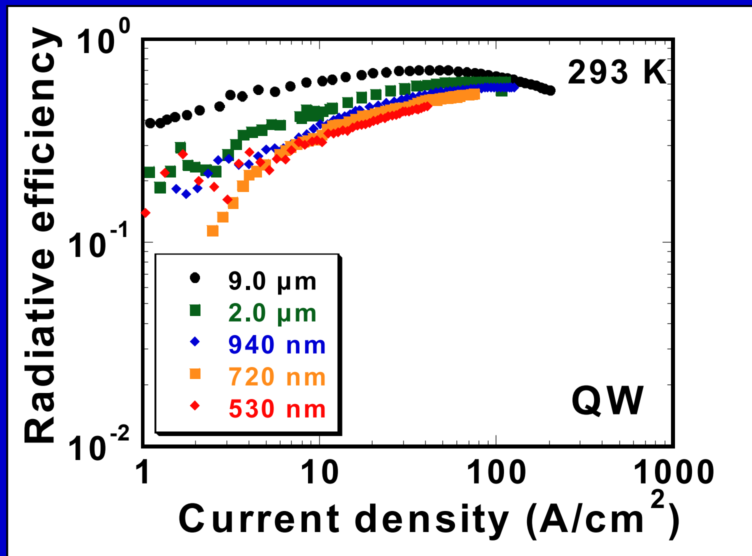


InGaAs quantum well:



Carrier diffusion + extraction efficiency:

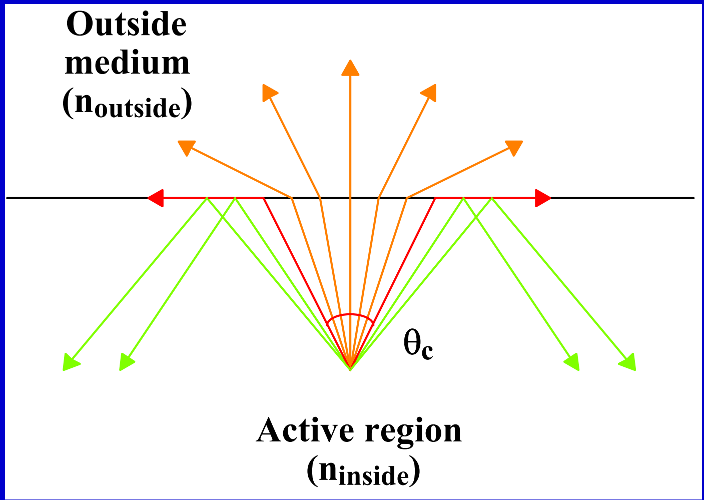




Fiore et al., PRB 2004

Extracting light from semiconductors

The problem of light extraction:



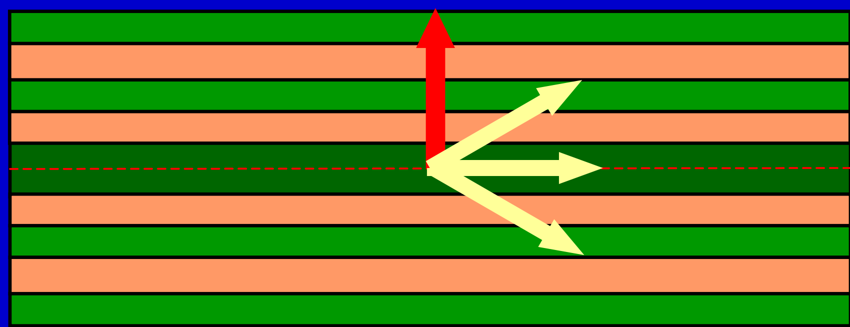
Total internal reflection

n(GaAs)≈3.5

$$\eta_{extr} = \frac{\Omega_c}{4\pi} \approx 2\%$$

Planar μ-cavity: no control in lateral directions

$$\Rightarrow \eta_{max} \approx 20\%$$



Need to change carrier-photon interaction so that light is generated only in useful directions

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Microcavities & QDs

Spontaneous emission rate:

$$W_{if} \propto |r_{12}|^2 \frac{g(E_2 - E_1)}{V}$$

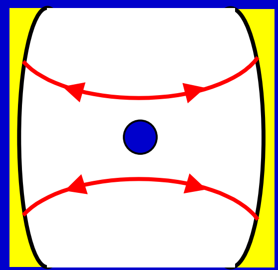
g(E): Opt. density of states per unit energy
V: Mode volume

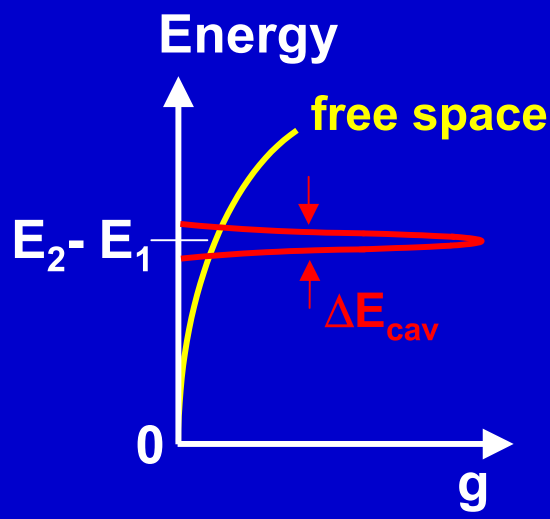
free space:

$$g_{FS}(E) = \frac{8\pi E^2}{h^3 c^3} V$$

cavity:

$$g_{cav}^{max} = \frac{1}{\Delta E_{cav}}$$





Sp. em. rate enhancement: *(Purcell, 1946)*

$$F_P = \frac{W_{cav}}{W_{FS}} \propto \frac{1}{\Delta E_{cav} V} \frac{1}{E^2} \propto Q \frac{\lambda^3}{V}$$

$F_P >> 1$ ⇒ $\eta \approx 100\%$

(all photons emitted in cavity mode)

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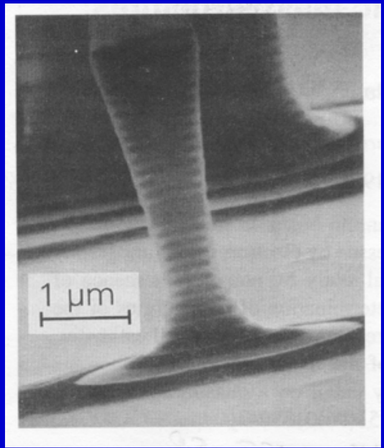
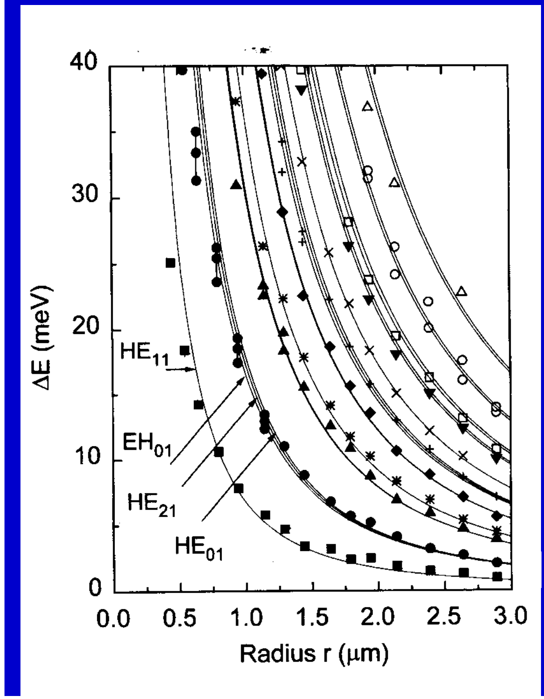
Electrical injection?

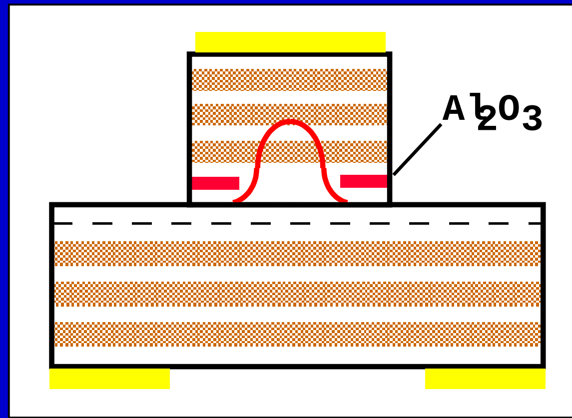
Micropillars (Gérard et al., PRL 1998) **:**



Strong optical confinement, optical excitation

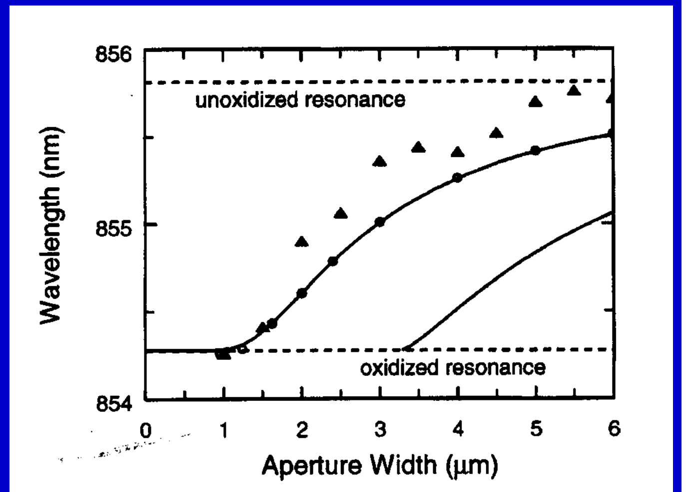


VCSELs:



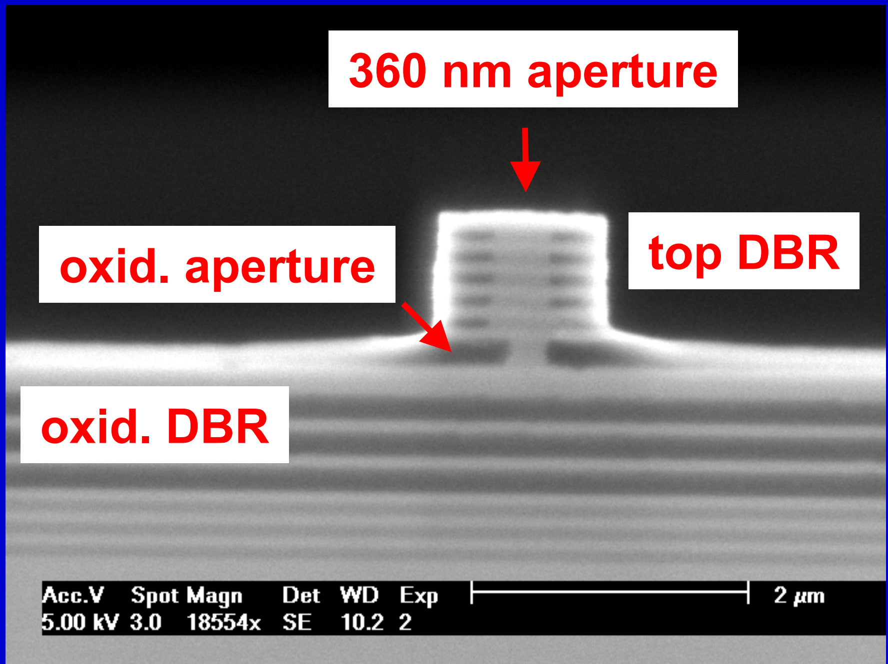
Low optical confinement, electrical inj.

Serkland et al., APL 2000:



Strong optical confinement, <u>and</u> electrical injection?

3D microcavity LED

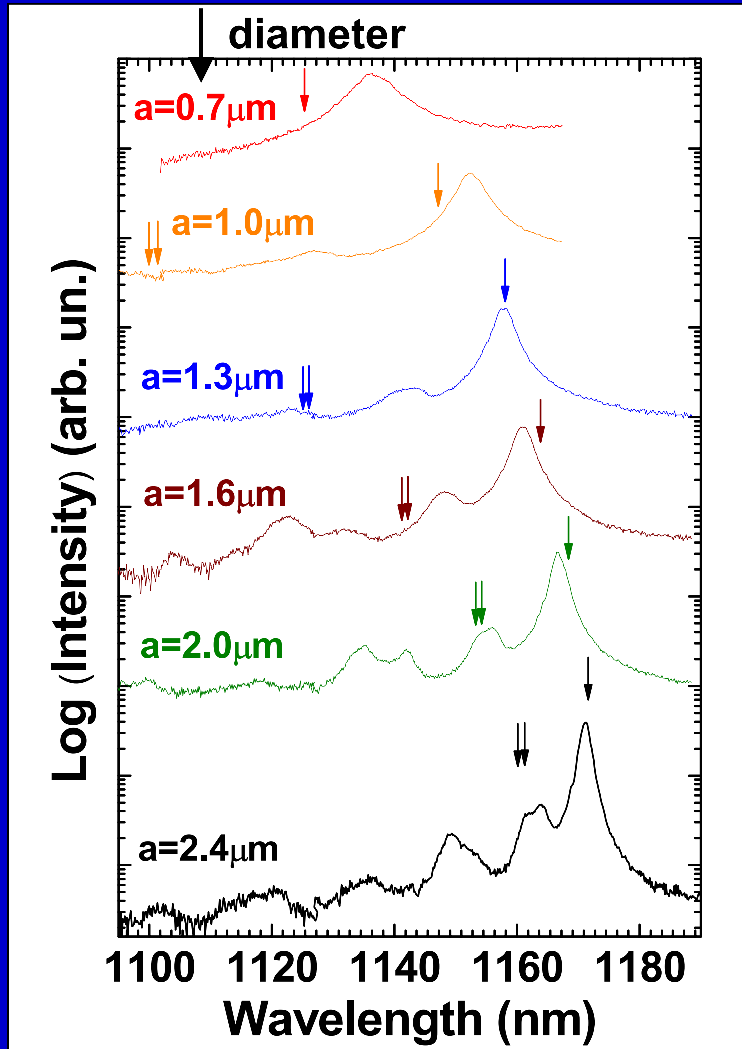


Design quality factor: Q=1000
Calculated Purcell effect for Φ=300 nm:

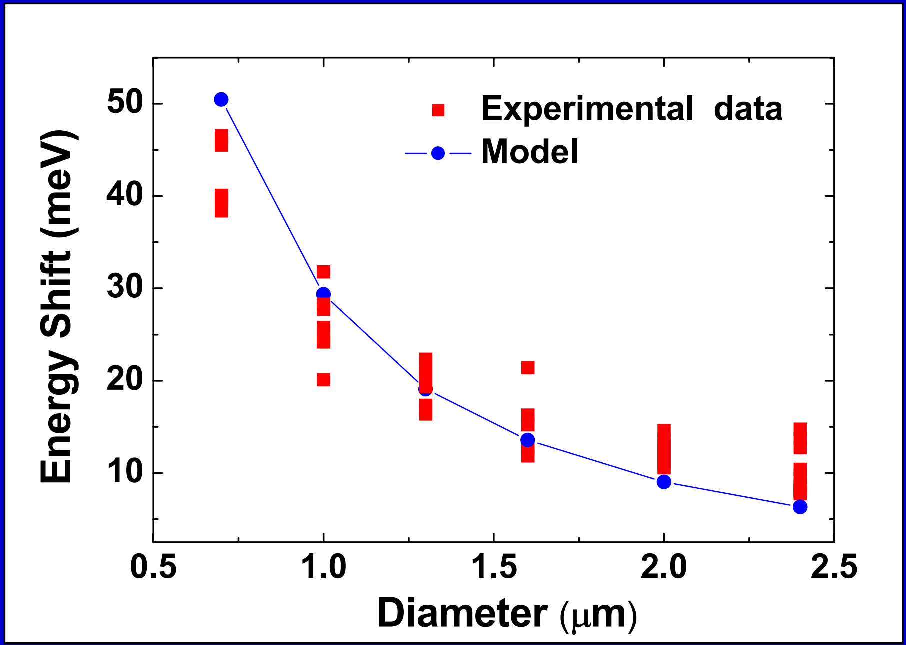
$$F_P = \frac{3}{4\pi^2}\frac{(\lambda/n)^3}{V_{cav}}Q \approx 40$$

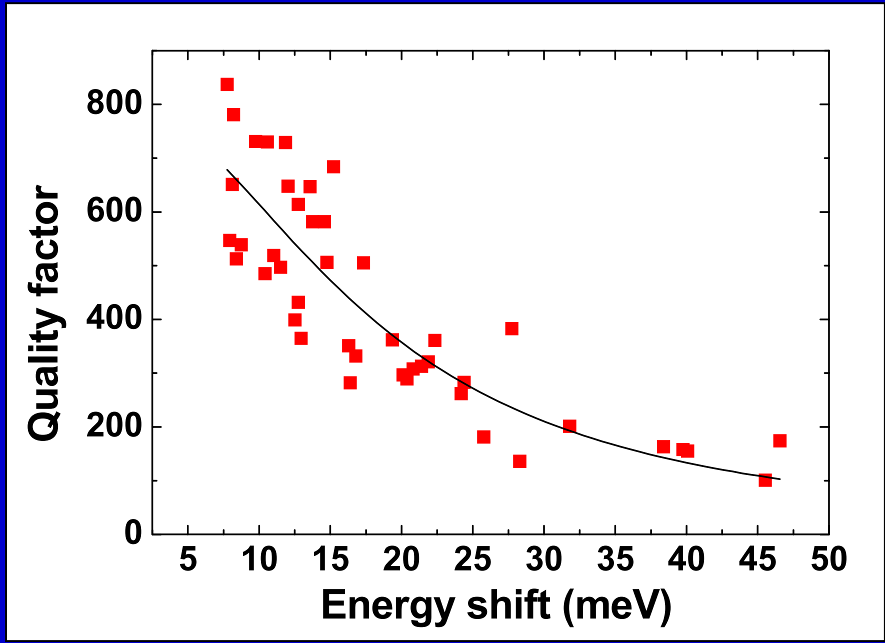
(Ideally!)

Spectroscopy of cavity modes under electrical pumping:



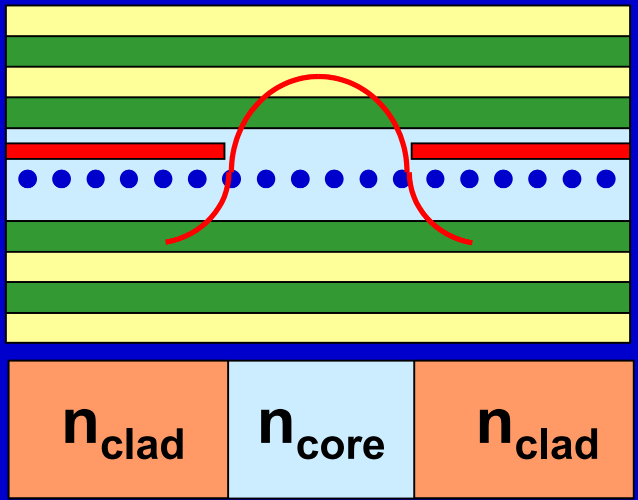
3D microcavity LED: Spectra





Zinoni et al., APL 2004

Effective index model:



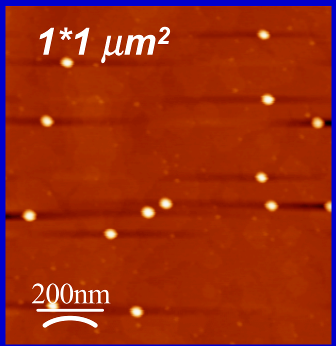
Loss increases with increasing confinement

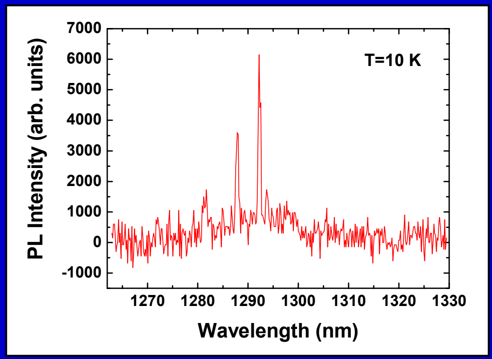
For F_p>>1: Need Q≈1000 for Φ<1 μm

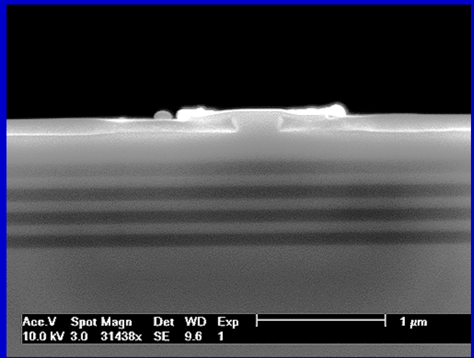
Summary

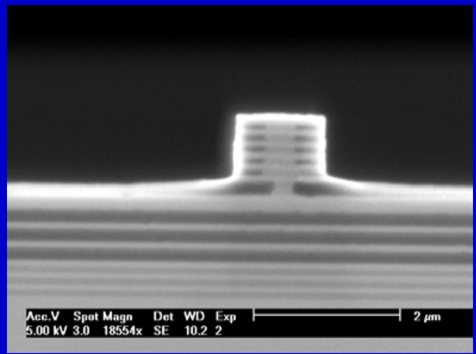
- Low growth rate ⇒ sparse, long-wavelength QDs
- Single QD spectroscopy *at 1300 nm*
- Carrier injection in <300 nm with oxidized apertures
- Strong optical confinement in ≈λ^3 volumes

Towards efficient single-QD LEDs









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QD