Quantum Dots for optical applications

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Tutorial developed with the support of ePIXnet

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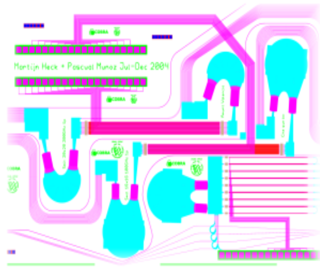
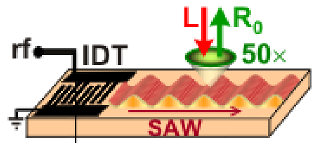
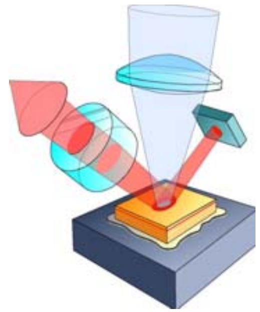
on
Photonic Integrated Components and Circuits

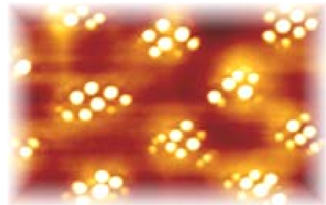


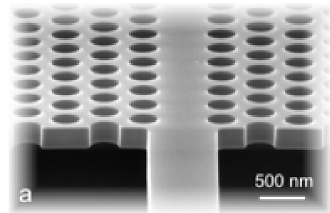


Integration of research on:

- Technologies for photonic VLSI
- Photonic Signal Processing
- Integrated Light Sources
- Advanced Materials
- Nanophotonics





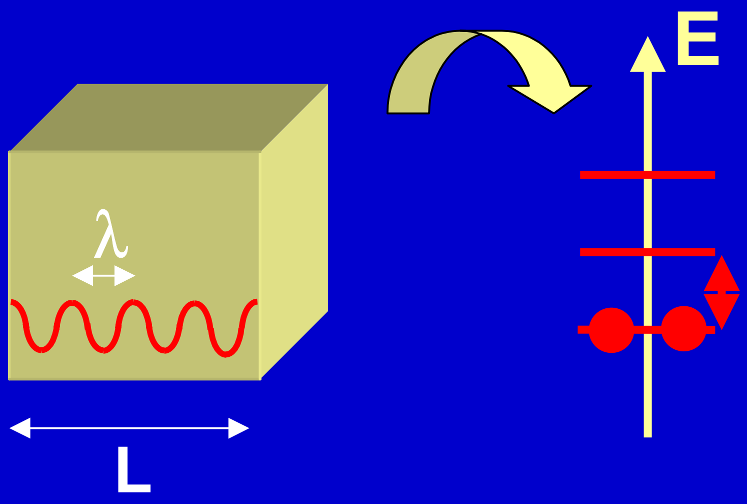


Through:

- Joint Research Activities
- Joint Education Programs
- Exchange of Researchers
- Dissemination of Knowledge

www.epixnet.org

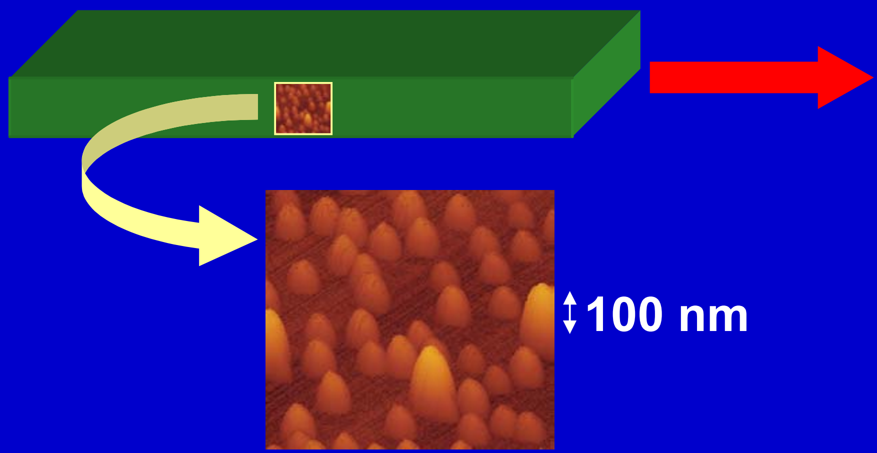
Quantum Dots



Electrons in GaAs, T=300K:

$$\Delta E > kT \Leftrightarrow L < \lambda \approx \frac{h}{\sqrt{2m^{*}kT}} \simeq 30\ \text{nm}$$

QD devices:



Outline:

- QDs: Dreams & reality
- The physics of single QDs
- Laser applications

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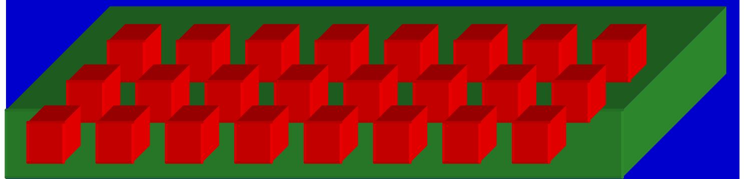
Why care about QDs?

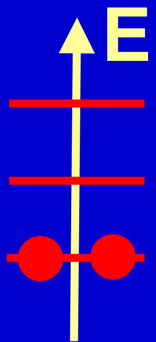
Or: The QD "dream"

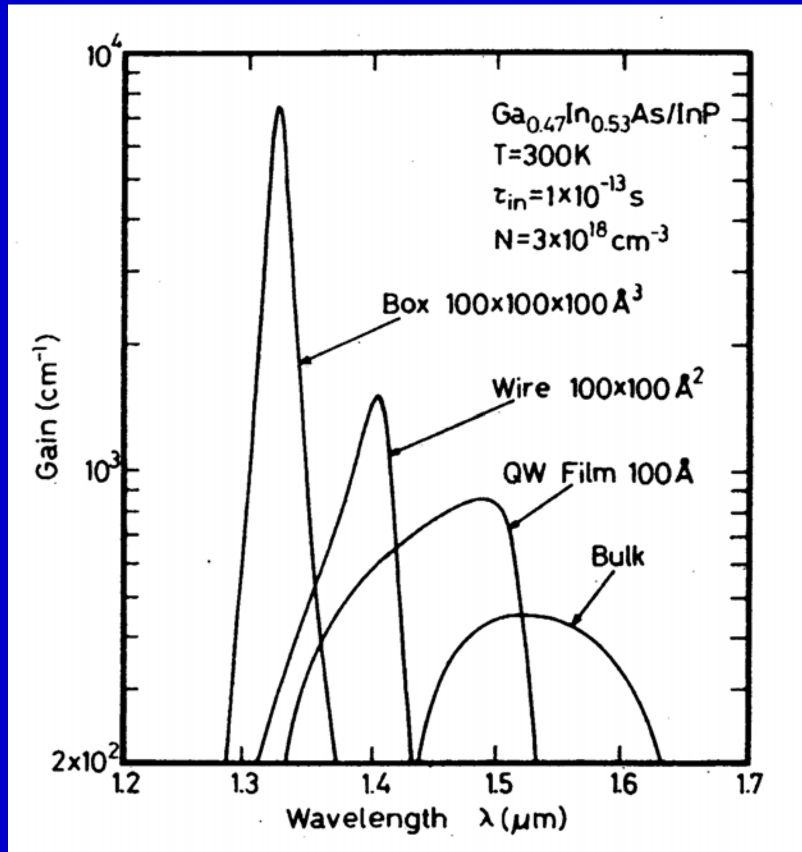
Narrower gain makes better lasers

Gain calculation:

Arakawa, Sakaki 1982
Asada et al., 1986







NB: Idealized picture !!!

- **Lower threshold current**
- **Lower temperature sensitivity**
- **Larger modulation bandwidth**

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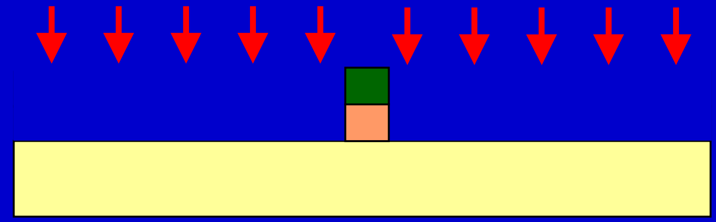
Real QDs

Or: The shattered dream?

Nanostructure fabrication: Quantum Dots

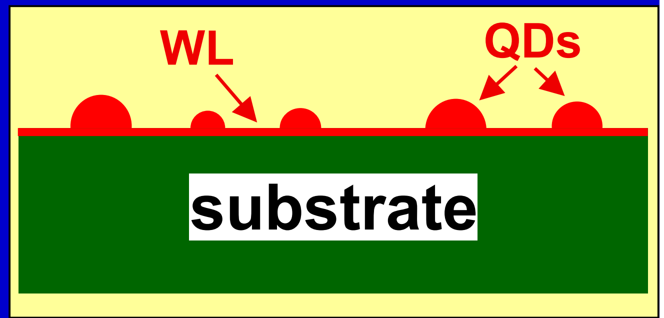
- **Top-down fabrication**

  ☹ Need **high-resolution lithography**
  ☹ Etching ⇒ **Nonradiative defects**

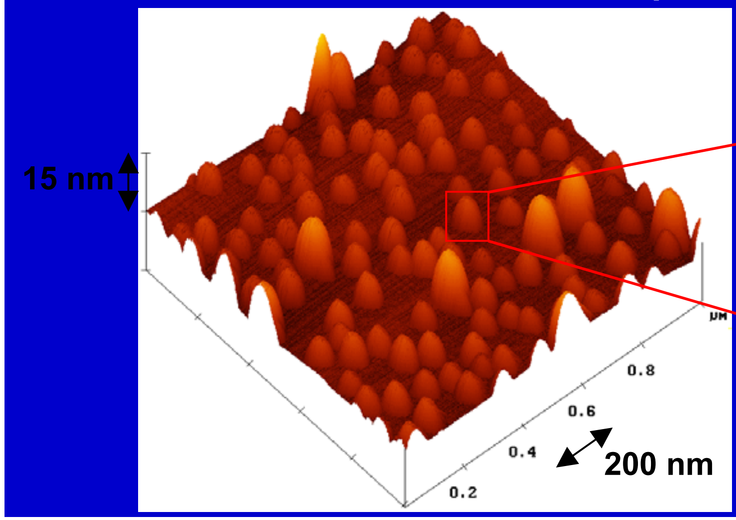


- **Bottom-up: Strain-driven self-assembly**

  ☺ High crystal quality ⇒ **radiative properties**
  ☹ Uncontrolled nucleation ⇒ **Size dispersion**

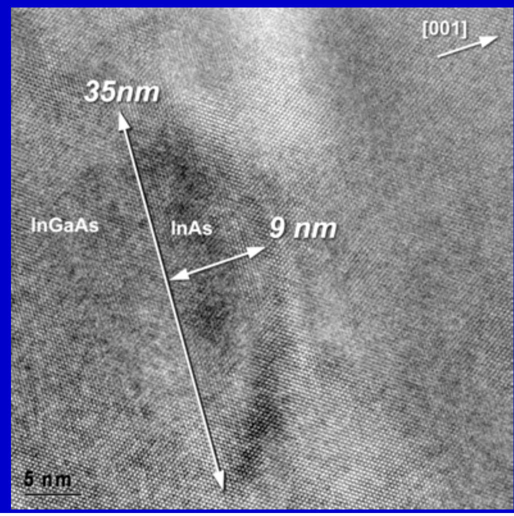


Example: InAs on GaAs (but also InAs on InP, Ge on Si, ...)

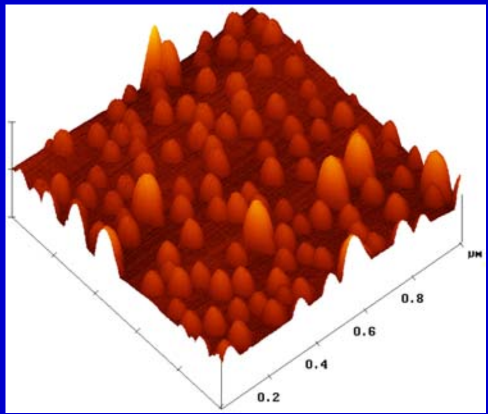


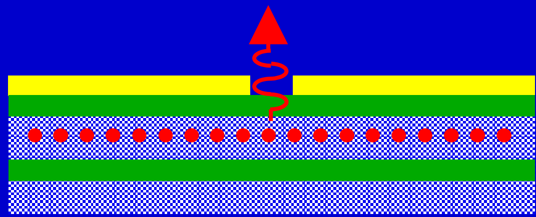
High *local* In content

⇒ **1300 nm on GaAs**

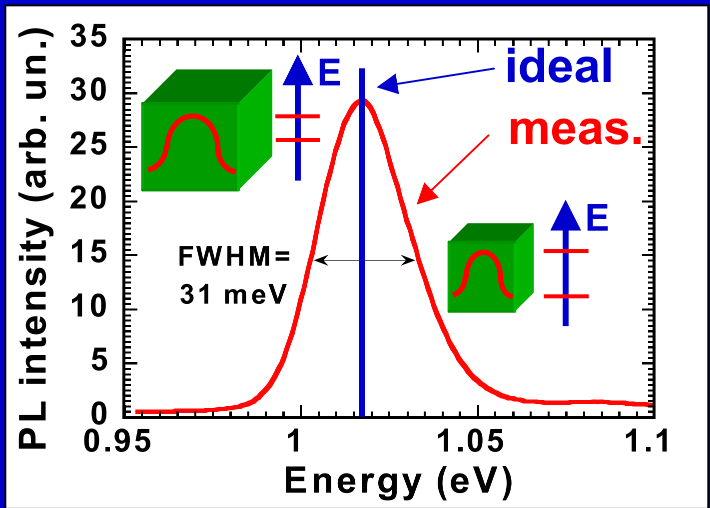


Inhomogeneous broadening

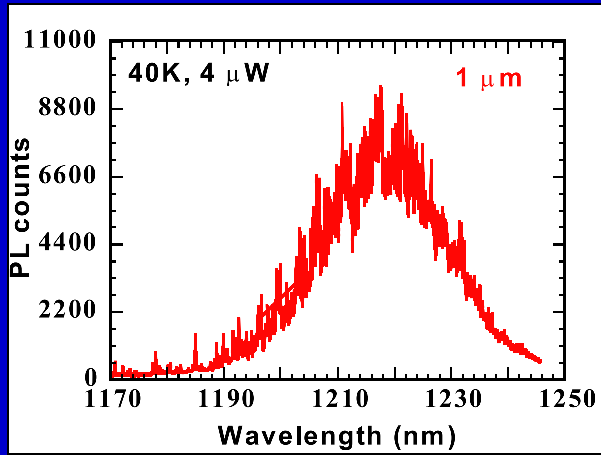




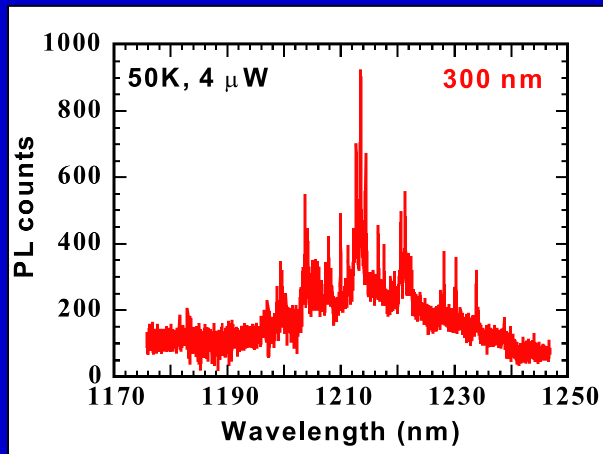
MacroPL at 5K:



1 µm diameter:



300 nm diameter:



Inh. broad.

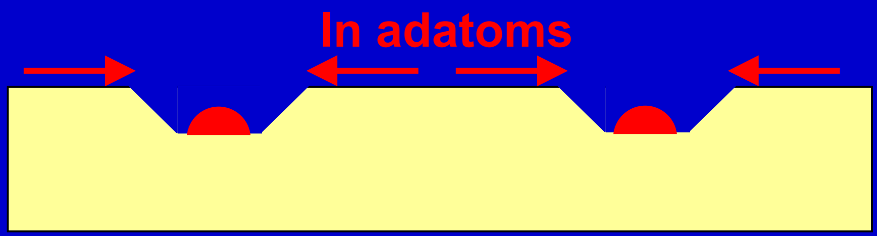
Gain FWHM:

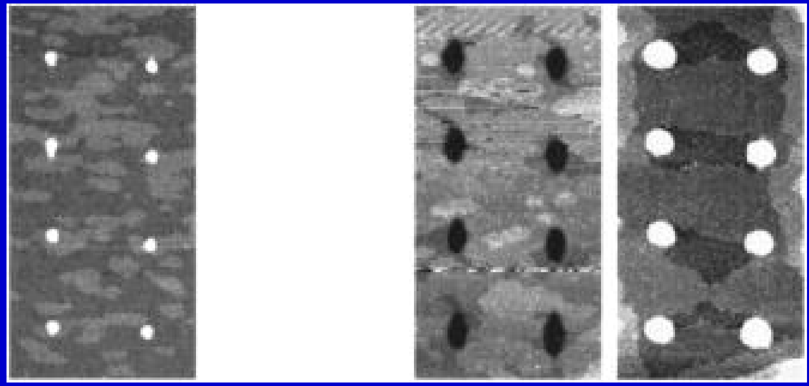
$\Delta E_{QDs} \approx \Delta E_{QWs}$

Dot density: 300 dots/µm^2

Can we do better? Controlling self-assembly

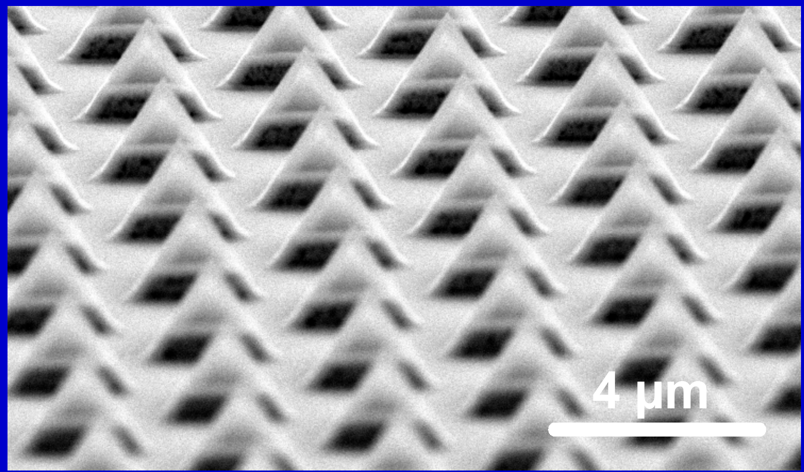
• SK growth on prepatterned substrates





Kohmoto et al., J. Vac. Sci. Tech. B 2002

• Growth-rate anisotropy driven growth:



Courtesy: E. Pelucchi, E. Kapon, EPFL

☺ Site control
☺ Improved unif.

Baier et al., APL 2004

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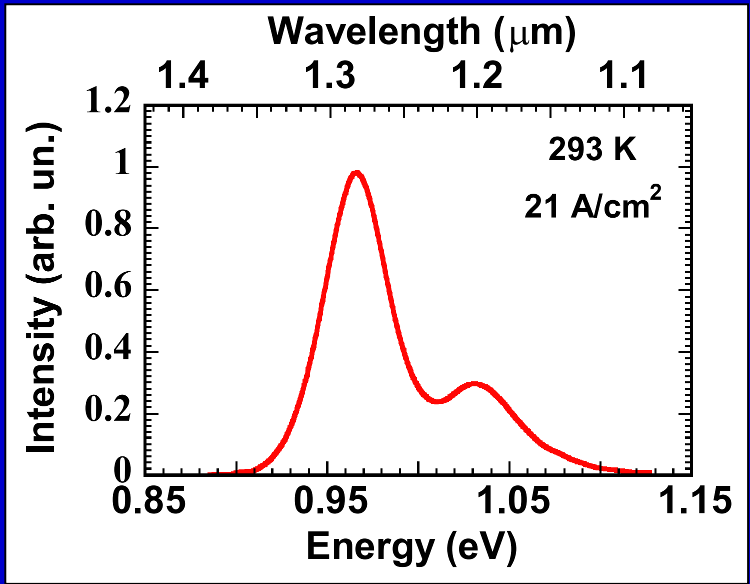
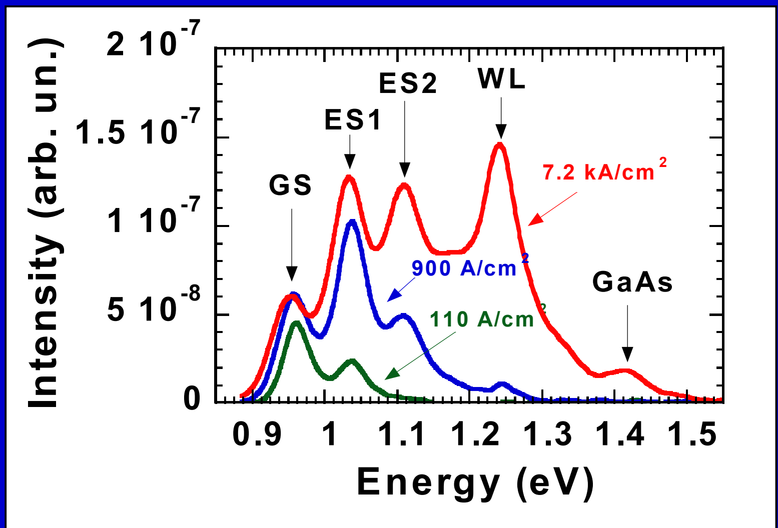
Radiative properties of self-assembled QDs



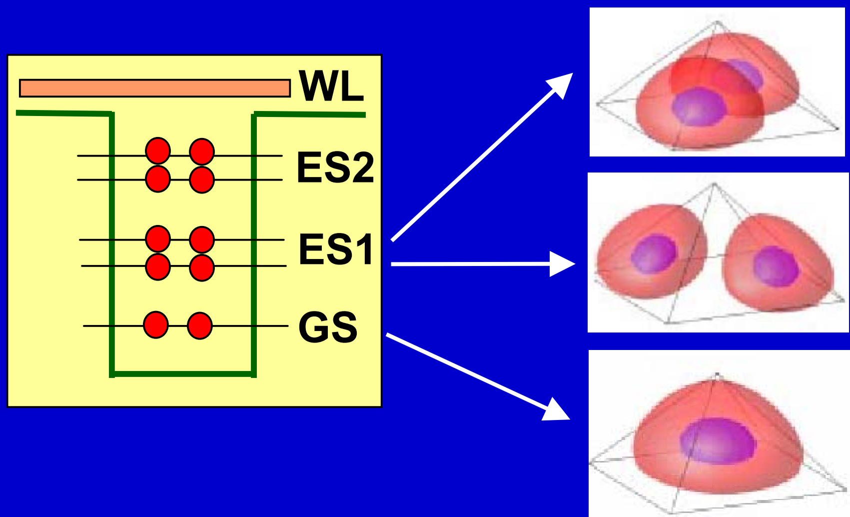
QD characteristics:

- 1300 nm emission on GaAs
- Radiative efficiency ≈20% at RT
- Long carrier lifetime ≈ 1ns
- Density: ≈$3x10^{10}$ cm^{-2}

Excited states:



A. Zunger, MRS Bulletin 1998



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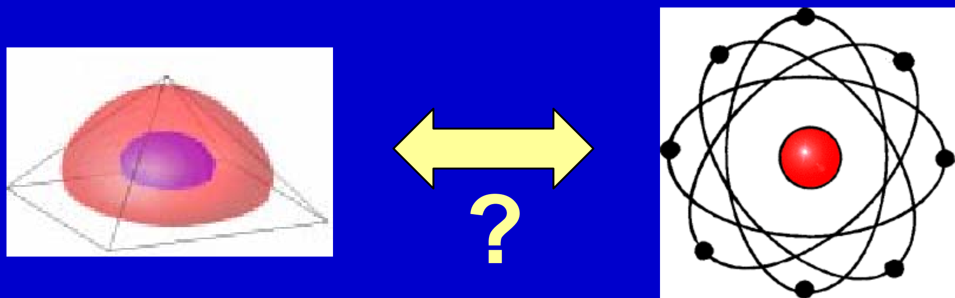
Single QD physics (and applications):

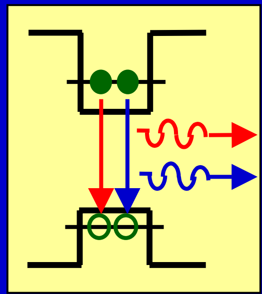
Like an atom?

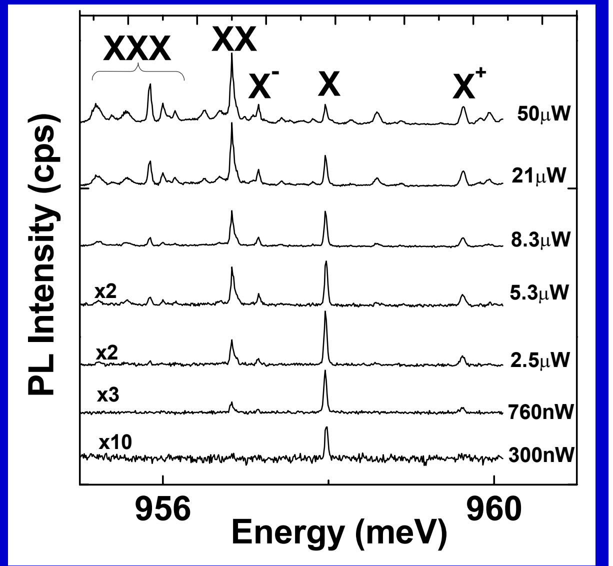


QDs behave as atoms...

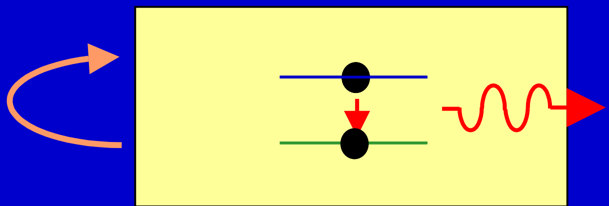
- Discrete electronic transitions
- Coulomb and exchange effects...

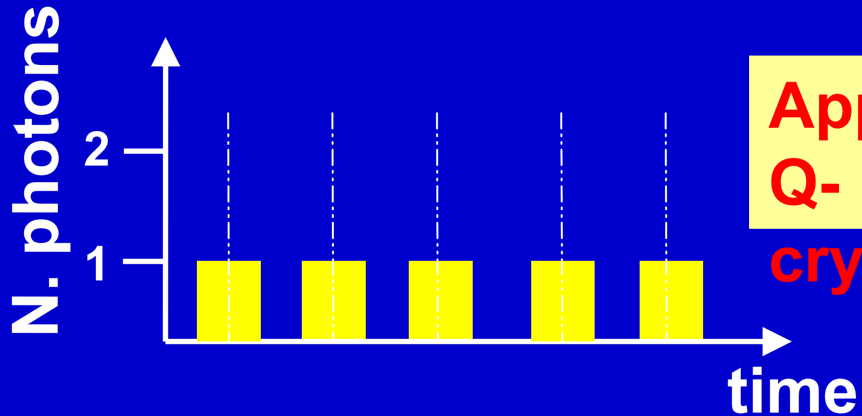
A solid-state toolbox for optical spectroscopy





- Single QDs generate single photons





Application to Q-cryptography

See invited talk by JM Gérard this afternoon

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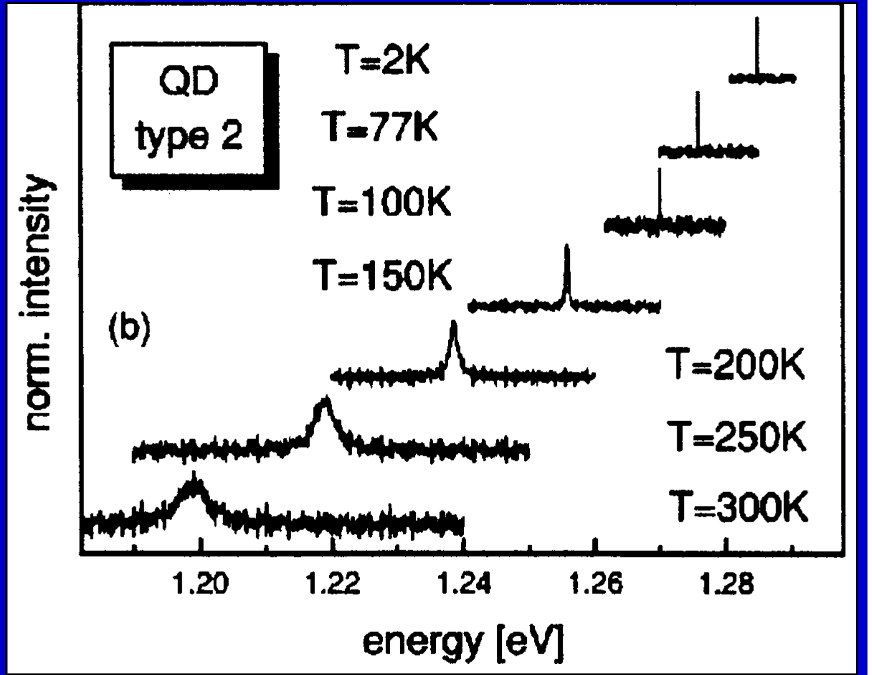
QDs do *not* behave as atoms...

Homogeneous linewidth:

$$\Gamma = \frac{2\hbar}{T_2} = \frac{2\hbar}{\tau_{life}} + \Gamma_{phonon}(T) + \Gamma_{Auger}(n)$$

At RT: $\Gamma \approx$5-15 meV

Borri et al., PRL 2001
Birkedal et al., PRL 2001
Bayer et al., PRB 2002



(Bayer et al., PRB 2002)

Interaction with crystal and carriers must be considered

QD lasers (1):
The physics of a different laser

A summary of laser performance

TTBOMK (To The Best Of My Knowledge)

On GaAs, at ≈1300 nm:

- J_{th}<30 A/cm^2 at RT (Huang et al. EL 2000, Park et al. PTL 2000)
- Linewidth enhancement factor <1 (several groups)
- 10 Gb/s modulation (Hatori et al. ECOC 2004, Kuntz et al., EL 2005)
- T_0>200 K *and* J_{th}<200 A/cm^2 (Shchekin EL 2002)

On GaAs (metamorphic), at ≈1500 nm:

- J_{th}≈1.5 kA/cm^2 at RT (Ledentsov et al., EL 2003)

On InP at ≈1550 nm:

- J_{th}<400 A/cm^2 at RT (Saito APL 2001, Wang PTL 2001)
- Linewidth enhancement factor <3 (Ukhanov et al., APL 2002)
- 10 Gb/s: -
- T_0=84 K (Schwertberger PTL 2002)

see also A. Kovsh's talk Fr A1-1

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The quantum side of QD lasers

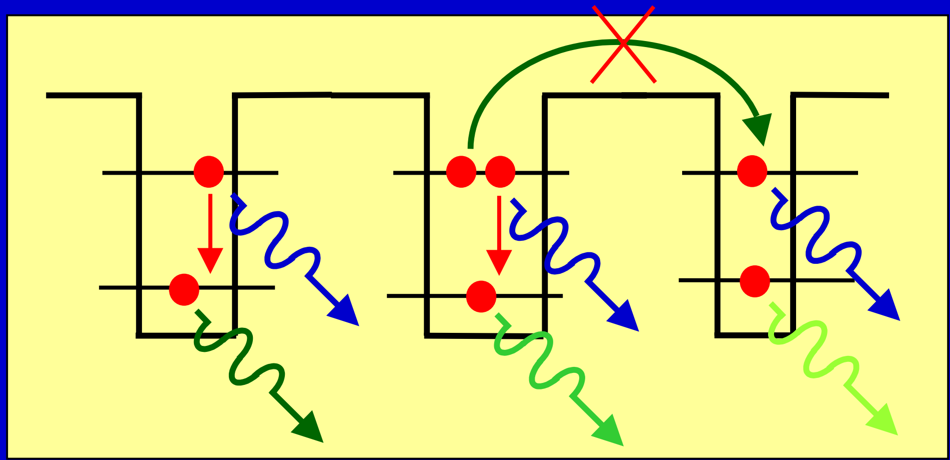
Quantum Dots: Are they really different *(better?)* than QWs?

Fact:

Inhomog. + homog. broadening makes gain linewidth " QWs

... But still it is a different laser!

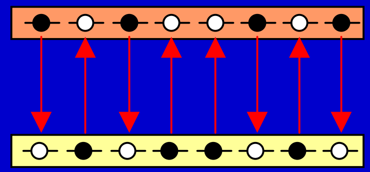
Confinement-related aspects:



- **Discrete n. states**
  - **Low J_{tr}**
  - **Low max gain**
- **Excited states**
  - **Intraband dynam.**
- **Localization**
  - **Thermal equil.?**

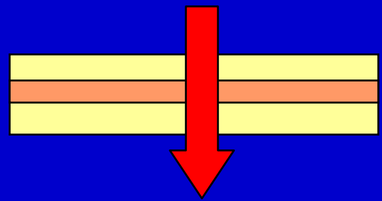
The role of the density of states

Transparency current:



$$I_{tr} \propto \frac{\rho(E)}{\tau}$$

Maximum gain per pass:



$$g_{max} = \frac{\pi e^2 x_{cv}^2 \omega}{e_0 n c} \rho(E)$$

1300 nm QDs on GaAs:

$$\left(g_S = 3x10^{10}\,cm^{-2}, \Delta E_{inh} = 20\,meV\right)$$

$$\frac{\rho_{QD}}{\rho_{QW}} \approx \frac{\pi \hbar^2}{m^*} \frac{2 g_S}{\Delta E_{inh}} \approx 0.1$$

QDs have ≈10 times lower density of states →

- **Low transparency current**
- **Low max gain**

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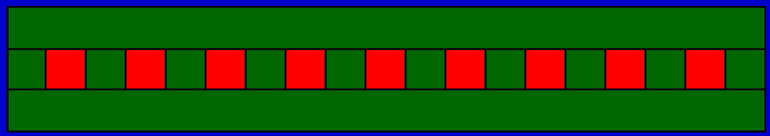
Record threshold current density

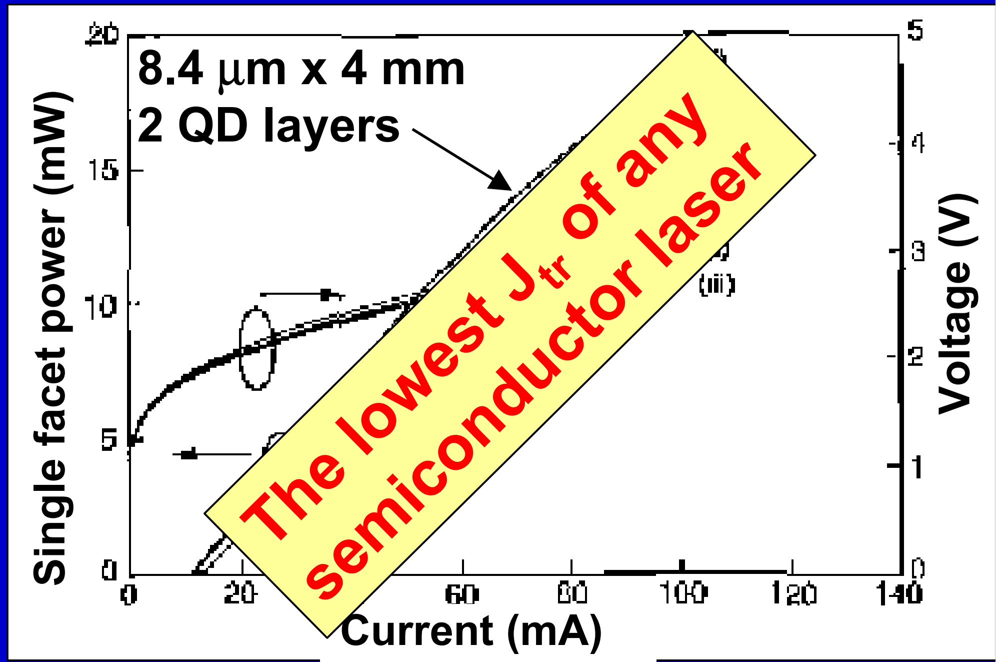


N quantum dots ⇒ 2N states

Room-temperature:

J_{th}=33 A/cm^2

J_{tr} = 9 A/cm^2



Huang et al., Electron. Lett. 2000

Theoretical estimate for J_{tr}:
(N_{QD}=2, g_S=3x10^{10} cm^{-2}, τ=800 ps)

$$J_{tr} = N_{QD}\frac{eg_S}{\tau} = 12\ \mathrm{A/cm^2}$$

BUT: Modal gain per QD layer ≈ 3-4 cm^{-1}

- Low-loss cavities
- Stack many layers

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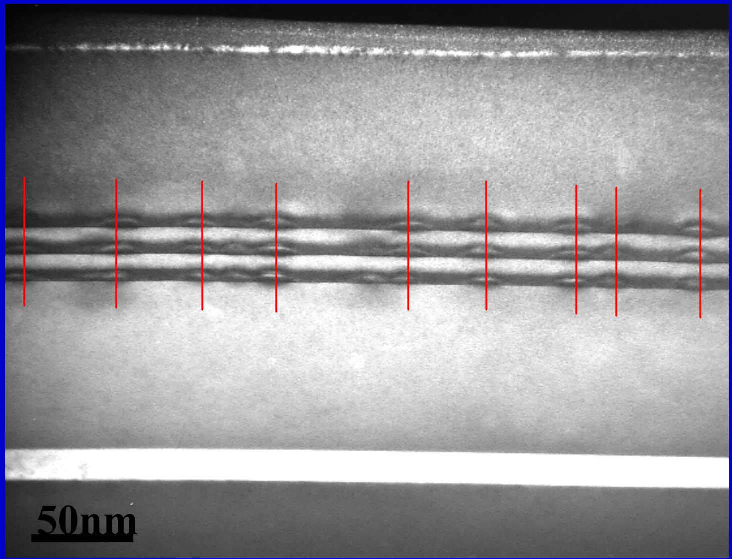
Gain limitations

Strain issues in QD stacking

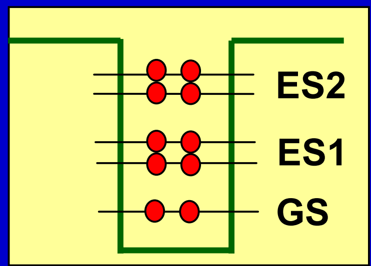


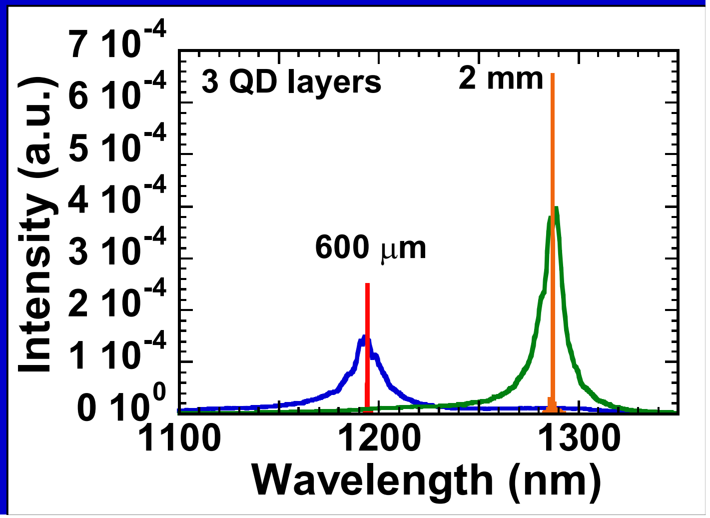
- **Strain compensation** *(Zhang, APL 2003, Lever, JAP 2004)*
- **High-T capping** *(Ledentsov 2003, Liu APL 2004)*

→ **Stacking of >10 layers**

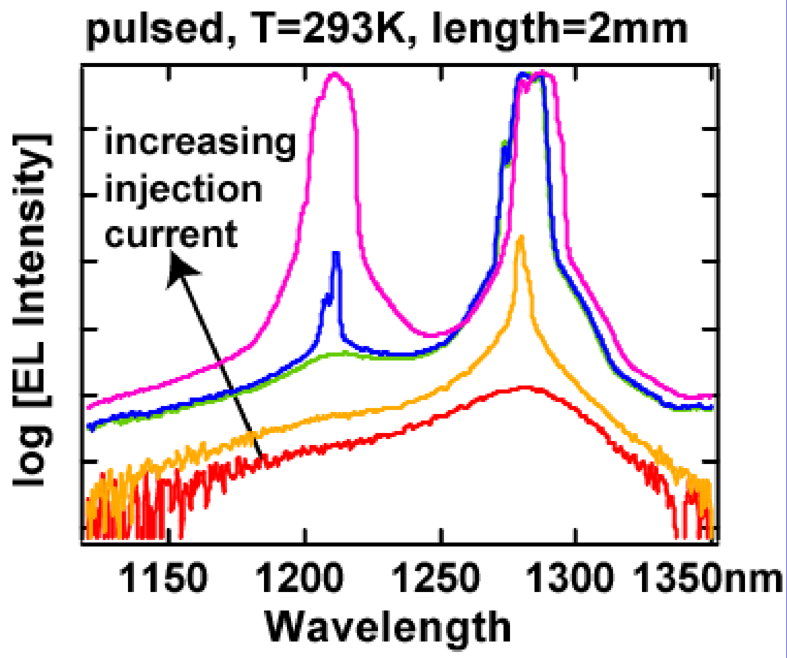
Ground state lasing only for low loss:

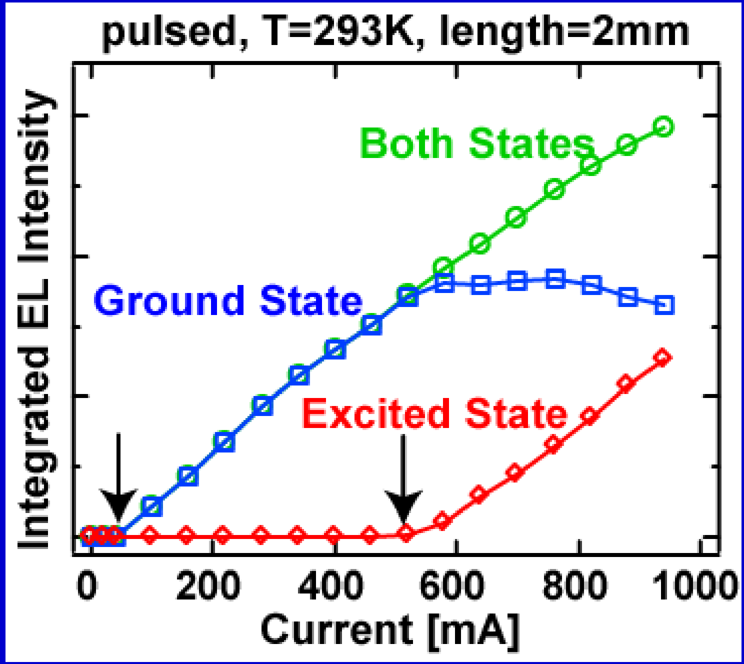
$$N_{QD} g_{th} = \alpha + \frac{1}{L} \ln \frac{1}{R}$$





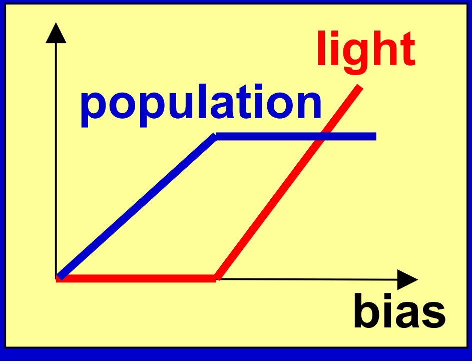
Dual-state lasing

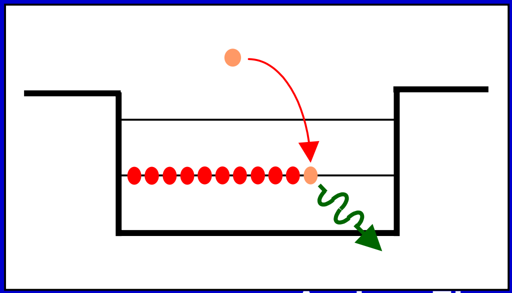




Markus et al., APL 2003

Violates population clamping theory ???





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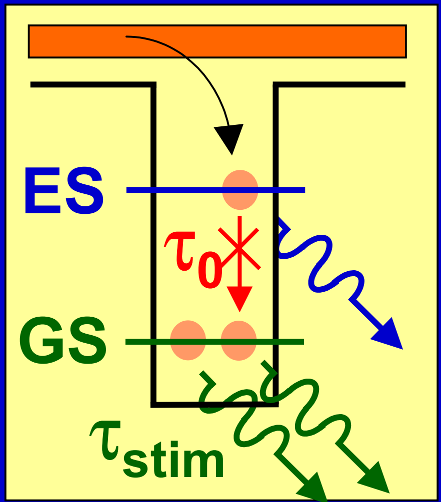
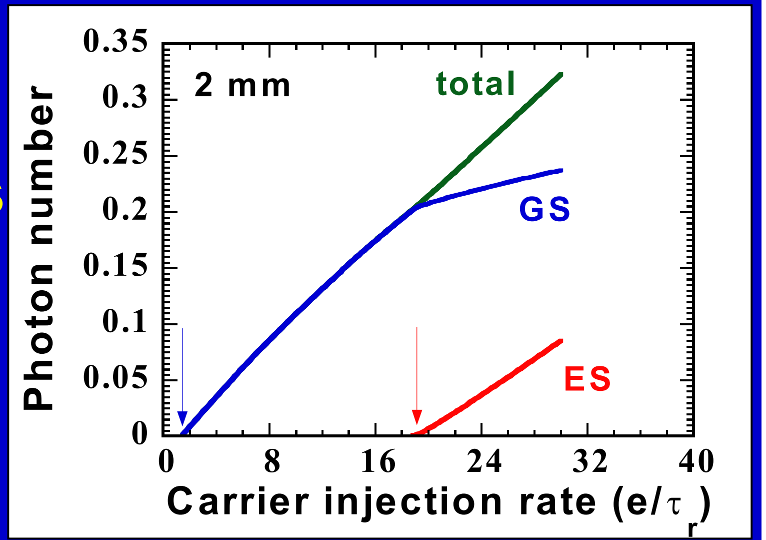
The role of intraband relaxation



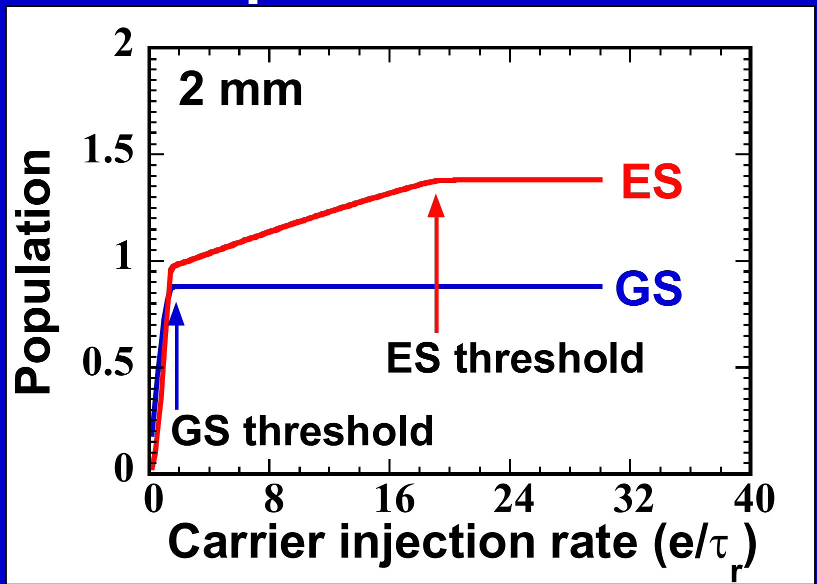
$$\frac{1 - f_{GS}}{\tau_0} \approx \frac{1}{\tau_{stim}}$$

$\Rightarrow$ ES population

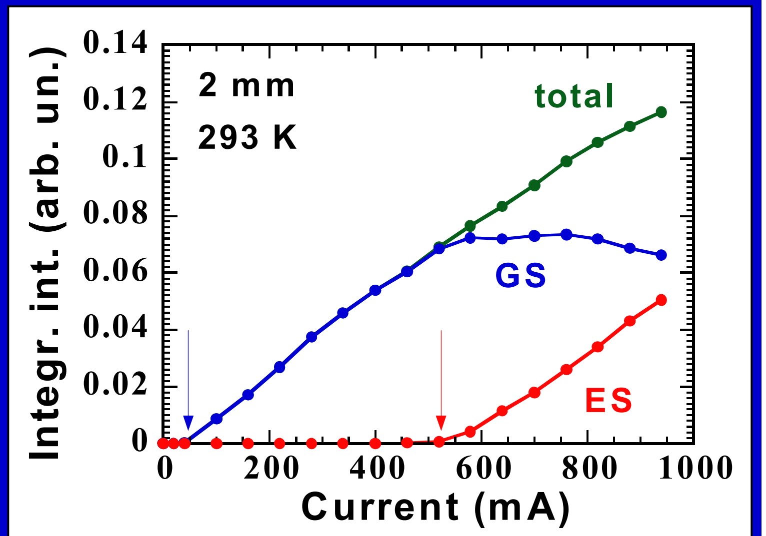
Model $\tau_0 \approx 8$ ps



Rate equation model:



Exper.



Predicted by Grundmann et al., APL 2000

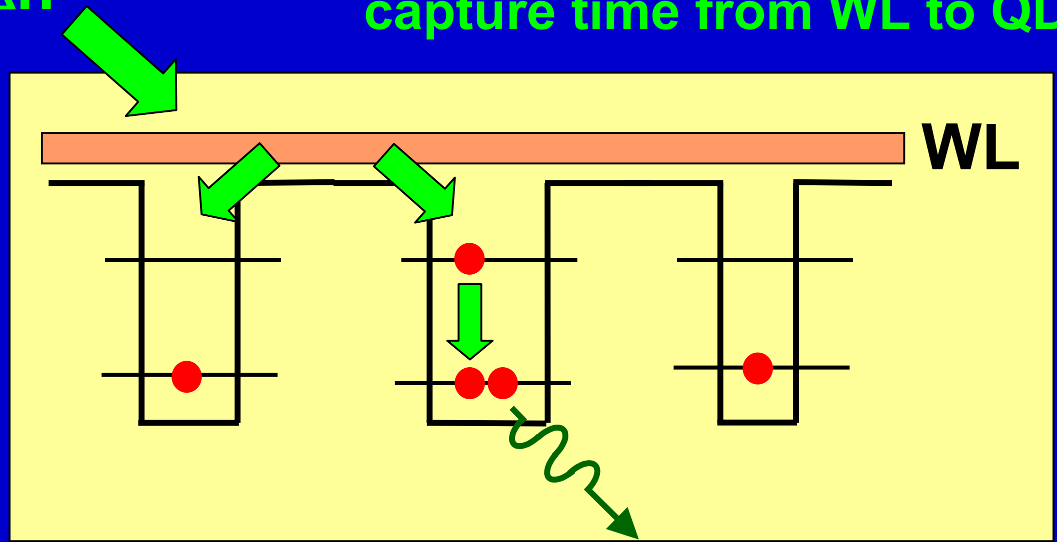
A more general view

Carrier accumulation in non-lasing states:

- Low differential gain → $g' = \frac{dg_{GS}}{dn_{tot}}$
- Large gain compression

Δn

capture time from WL to QD $\Rightarrow \Delta n_{WL}$



relaxation time from ES to GS $\Rightarrow \Delta n_{ES}$

capture into nonlasing QDs $\Rightarrow \Delta n_{nonlas\ QDs}$

$$\Delta n_{GS} << \Delta n_{tot} \Rightarrow g' = \frac{dg_{GS}}{dn_{tot}} \text{ small}$$

- Small f_{rel} in lasers
- High P_{sat} in SOAs

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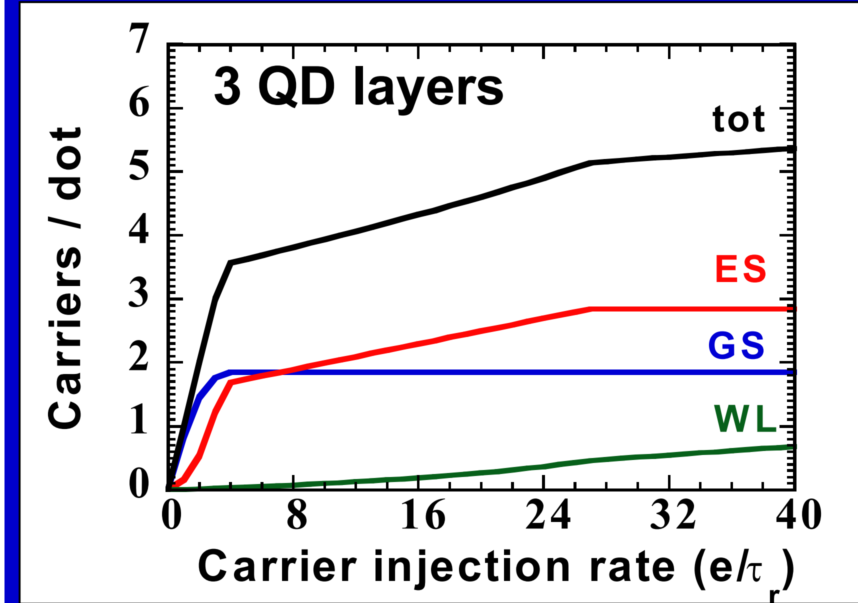
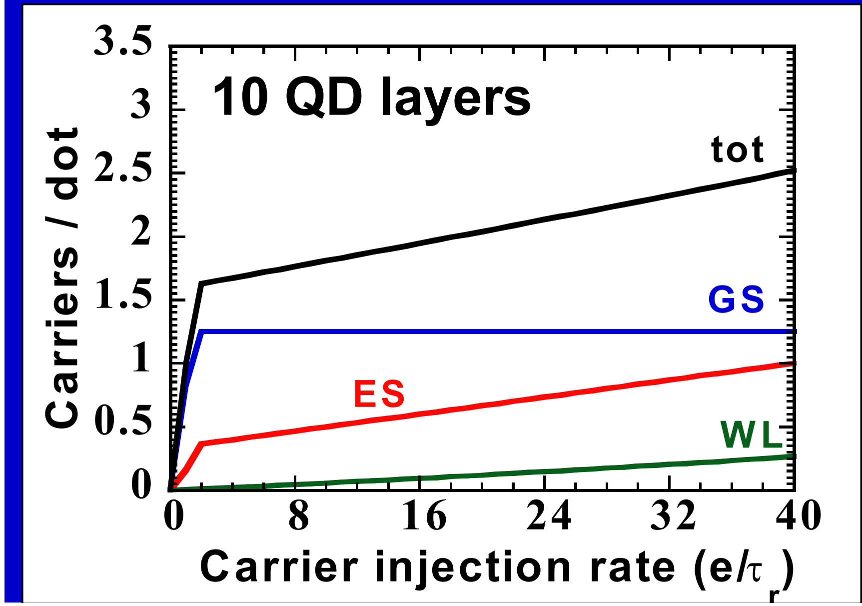
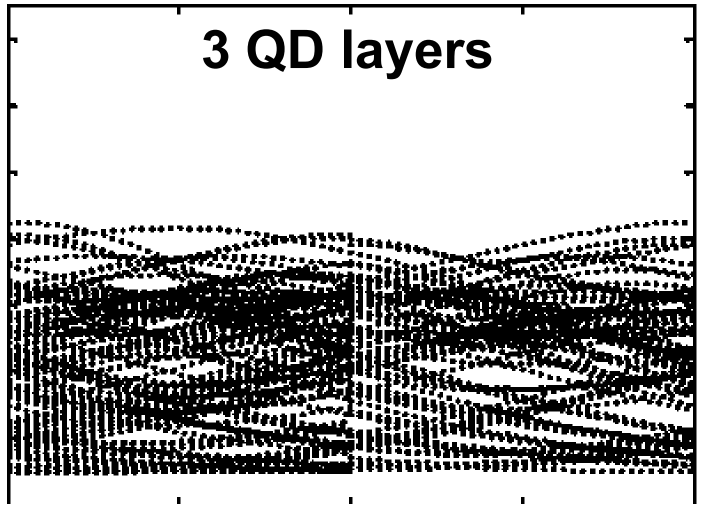
Modulation characteristics

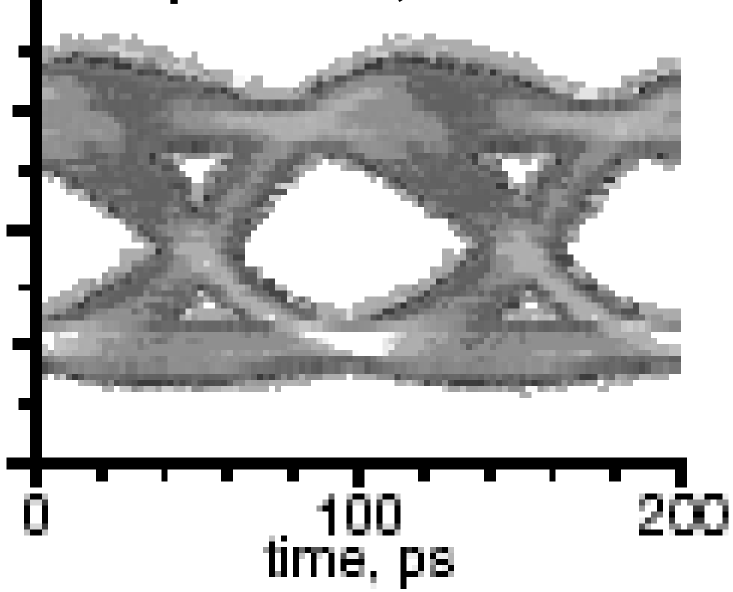




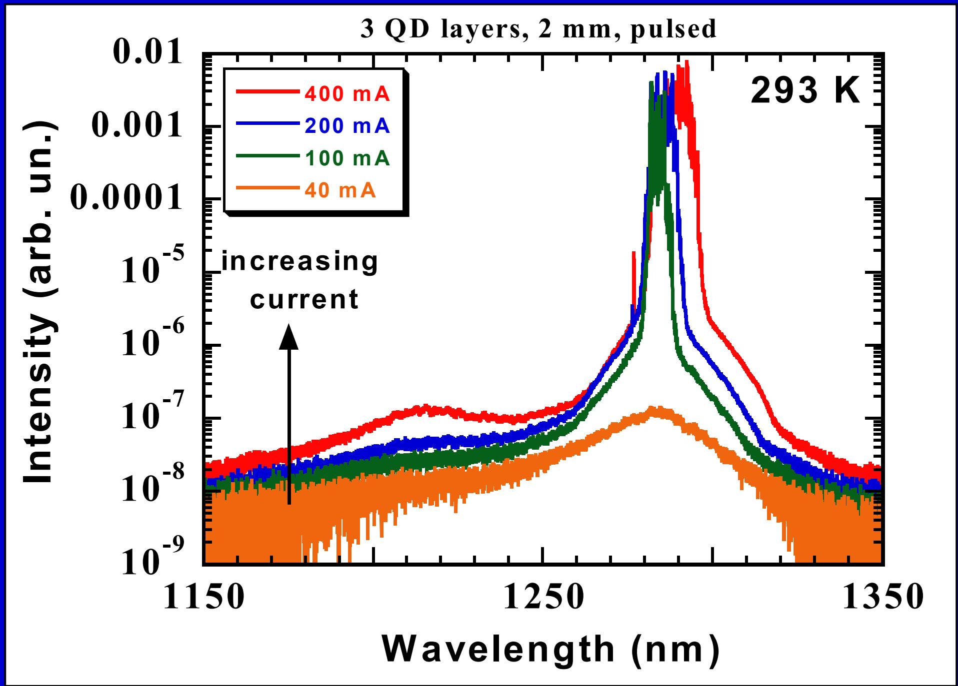
@10 Gb/s:

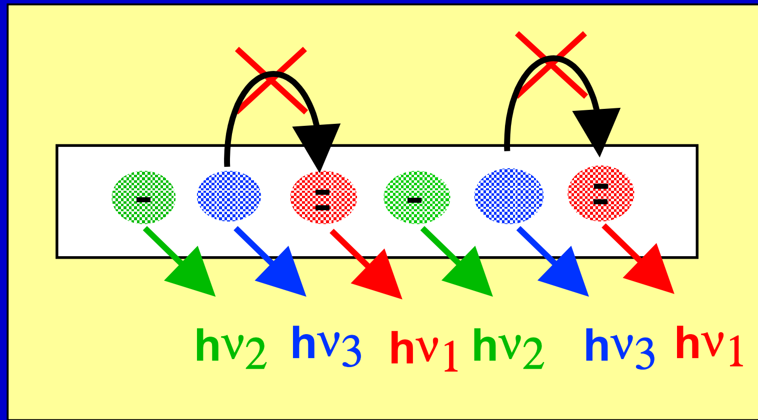


Exp.: Kuntz, EL 2005



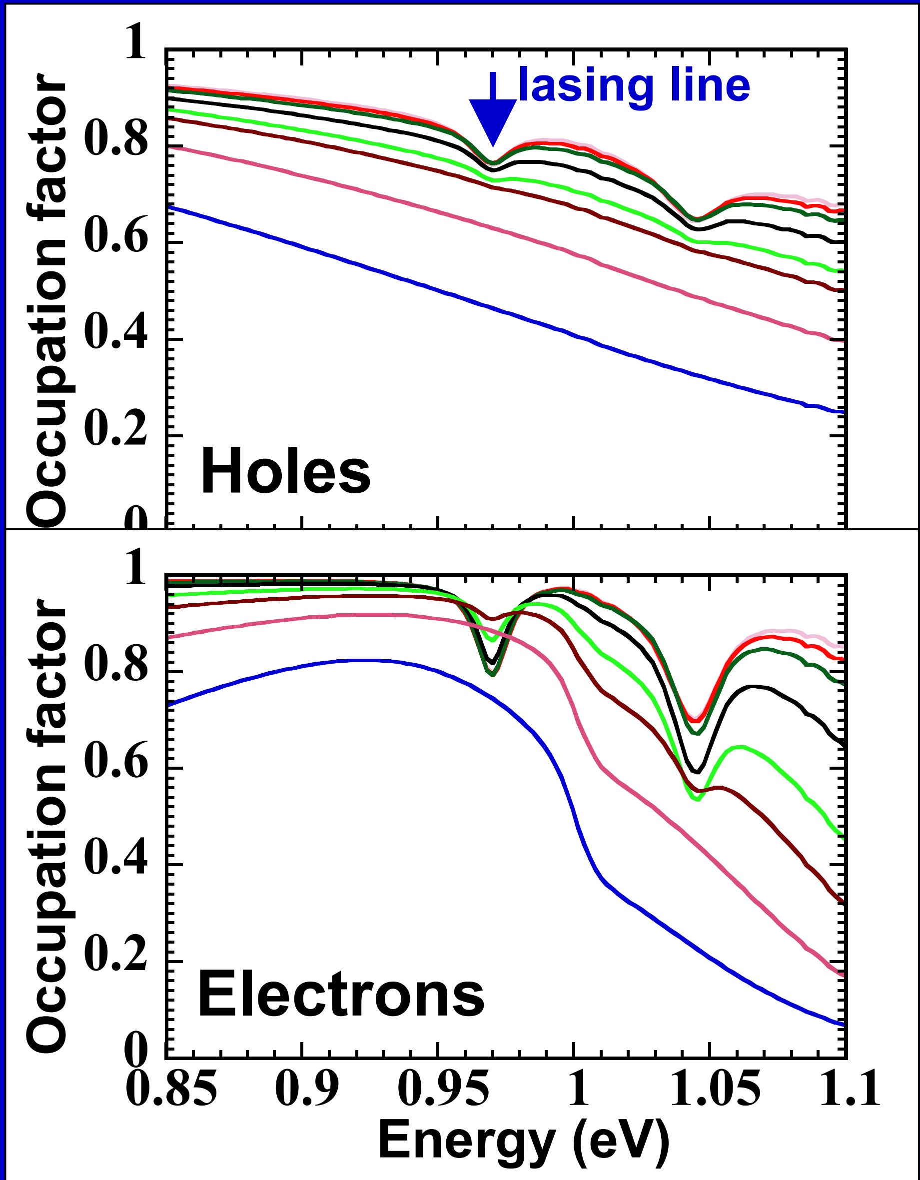
Thermal equilibrium?



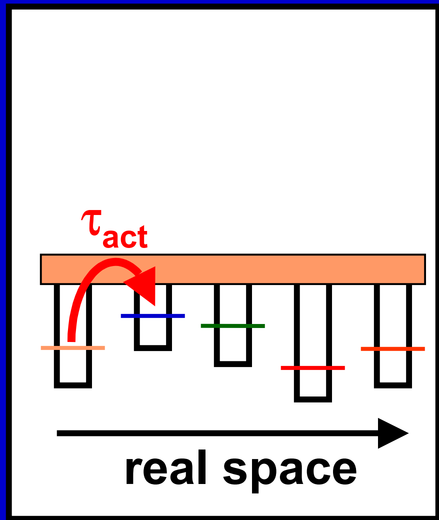


Inhomogeneous broadening +
absence of thermal equilibrium
⇒ Broad laser line = many ≈independent lasers!

Thermal equilibrium

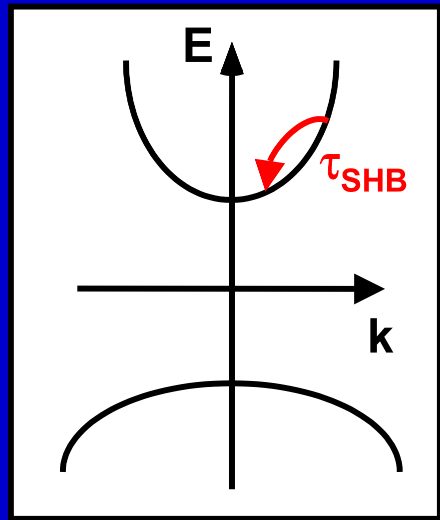


QDs:



τ_{act}>100 ps

QWs:



τ_{SHB}<1 ps

QDs more prone to non-equilibrium distribution

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QD lasers (2):
Prospects for application?

- Low threshold current
- Small linewidth enhancement factor
- Temperature performance

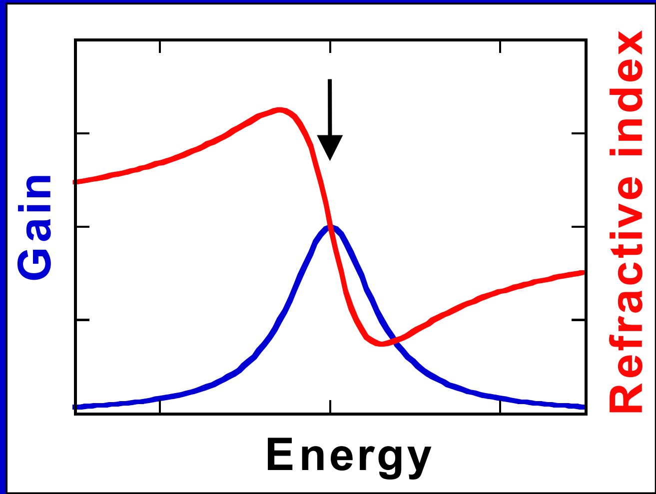
→ **Lasers**

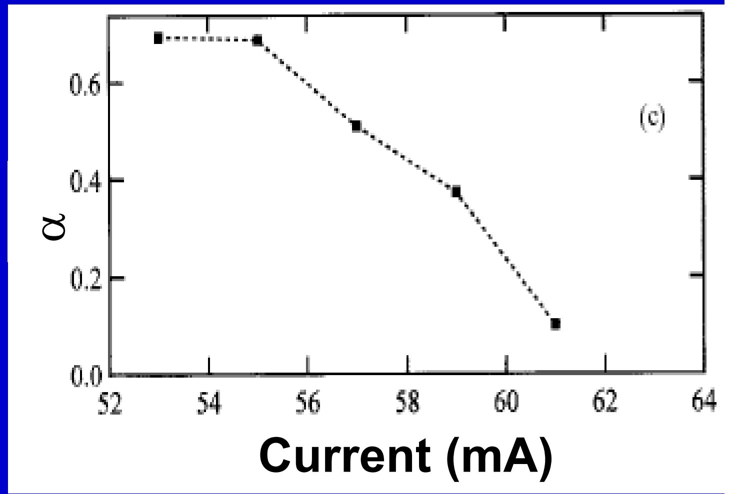
- Broad gain, large saturation power → **SOAs, SLEDs**

Linewidth enhancement factor in QD lasers

Ideally:

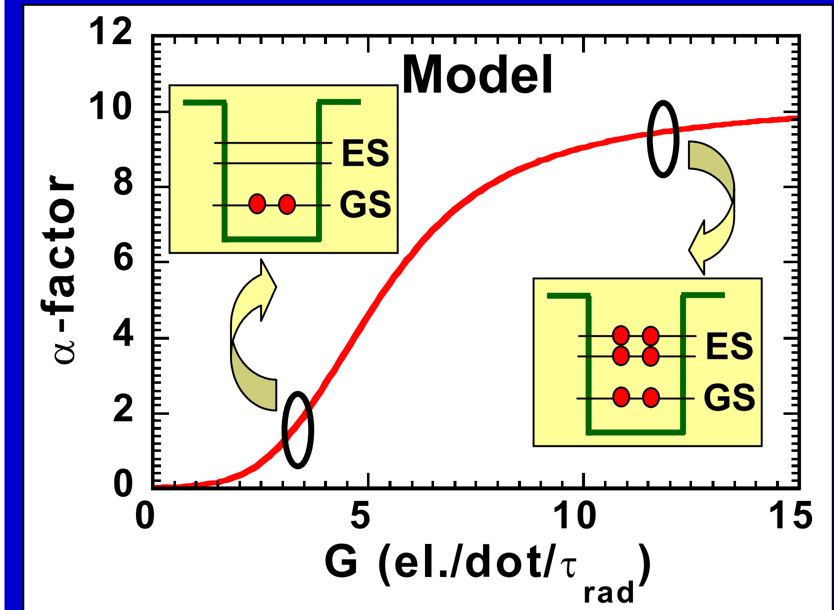
$$\alpha = \frac{4\pi}{\lambda} \frac{dn_{eff}/dN}{dg/dN} = 0$$

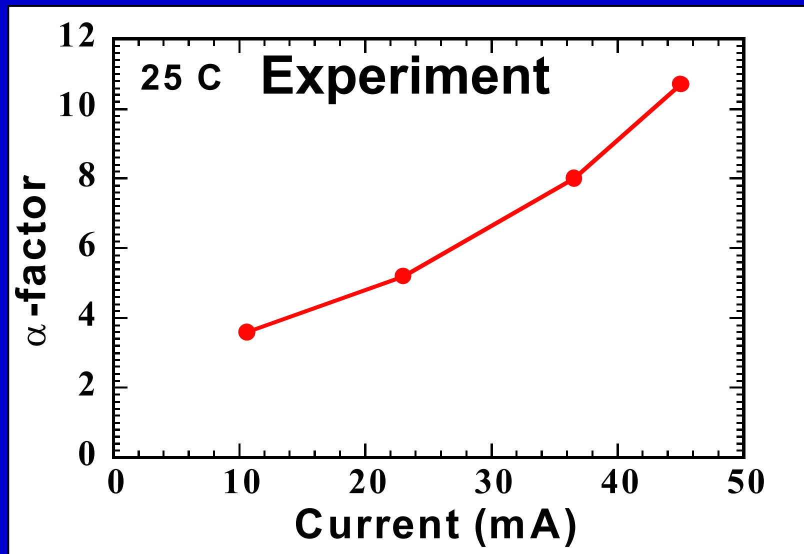




Newell et al., PTL 1999

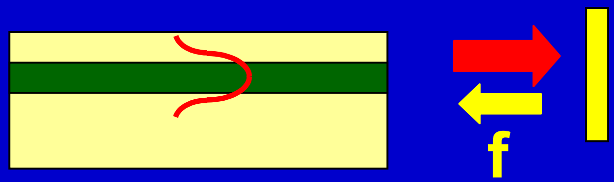
At high bias: Excited states!

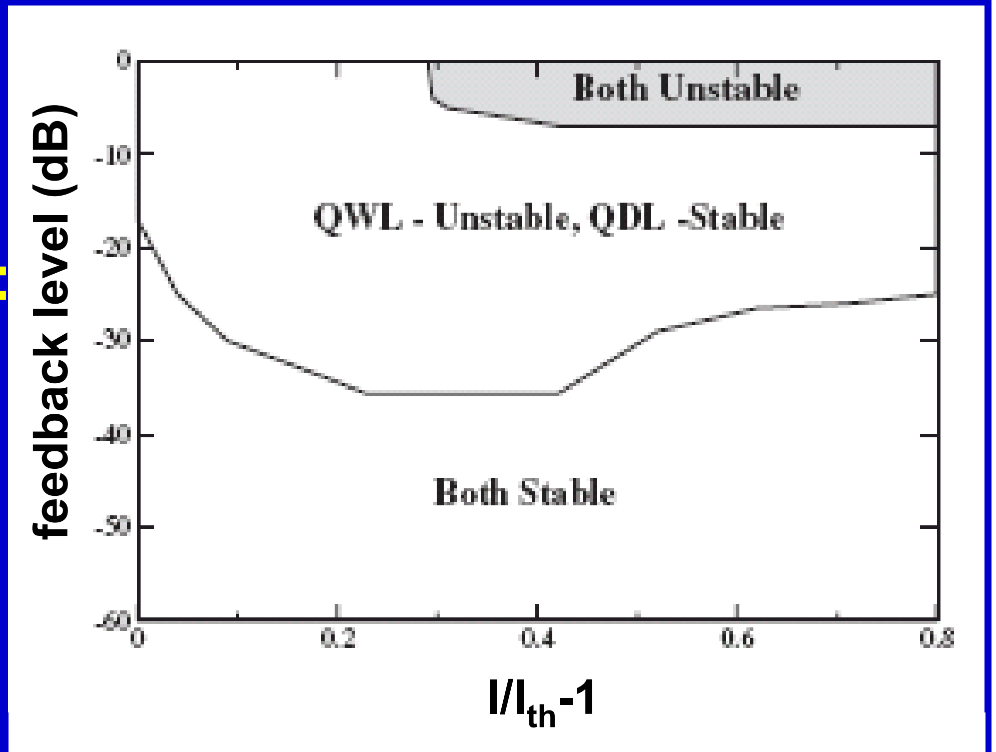




Markus et al., JSTQE 2003

Insensitivity to feedback





O'Brien et al, Electron. Lett. 2003

Coherence collapse threshold:

$$f_{crit} \propto \Gamma^2 \frac{1+\alpha^2}{\alpha^4}$$

α: linewidth enh. factor

Γ: damping rate

QDs:

- α small
- Γ large (gain compression)

} **Reduced feedback sensitivity**

→ **Potential for isolator-free modules**

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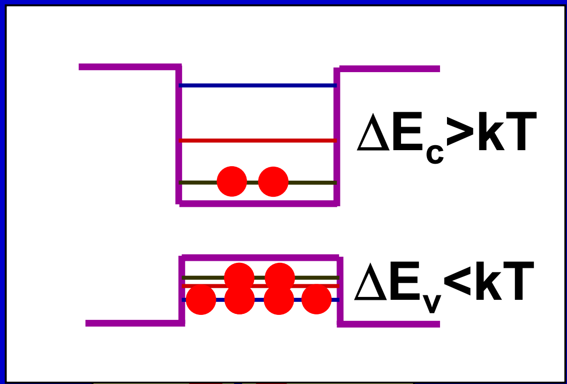
Temperature characteristics



Holes spread among closely-spaced levels

No thermal activation if ΔE>>kT

Shchekin et al., APL 2002

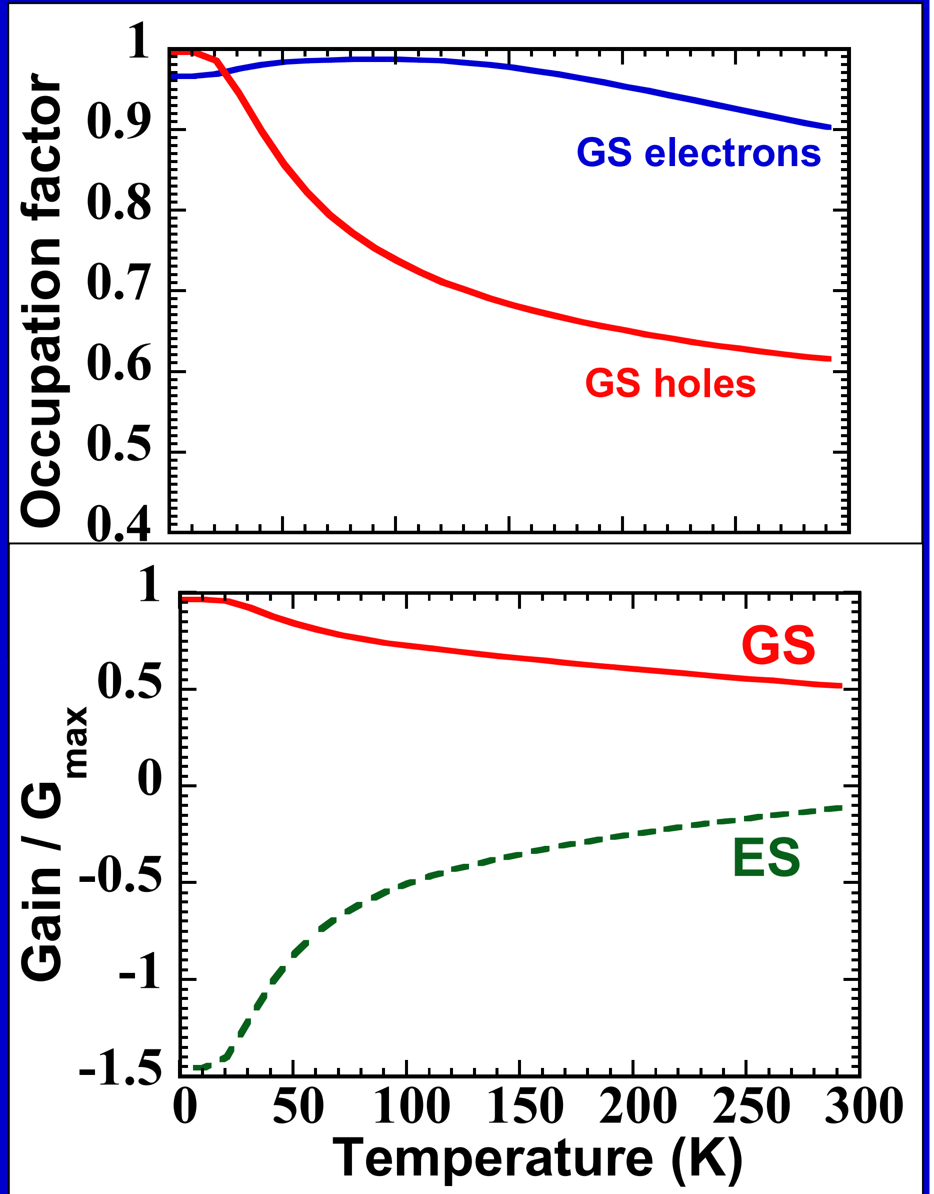
Matthews et al., APL 2002

Use p-doping

T-dependence fixed by electron distribution

T_0>200 K

(Shchekin EL 2002)

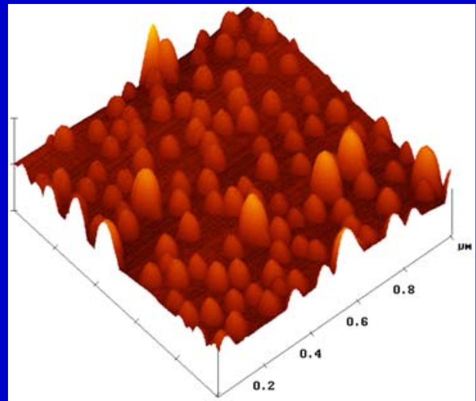


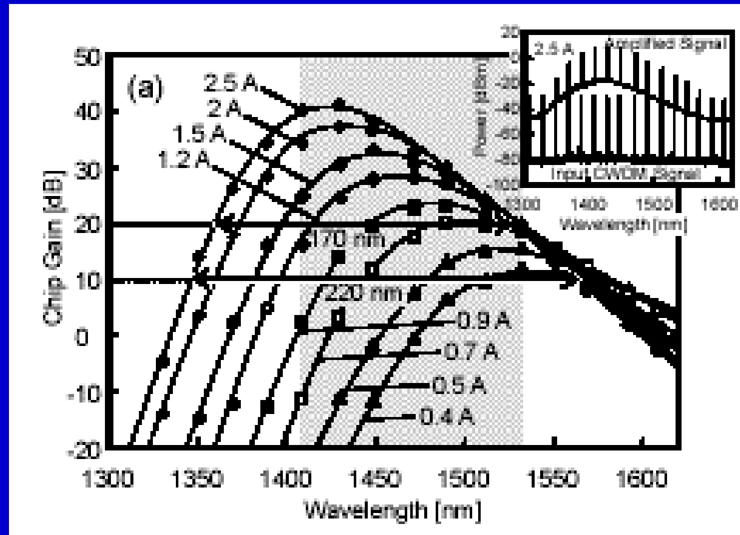
QDs as amplifiers

Size dispersion

⇩

Broad gain spectrum





Akiyama et al, OFC 2004

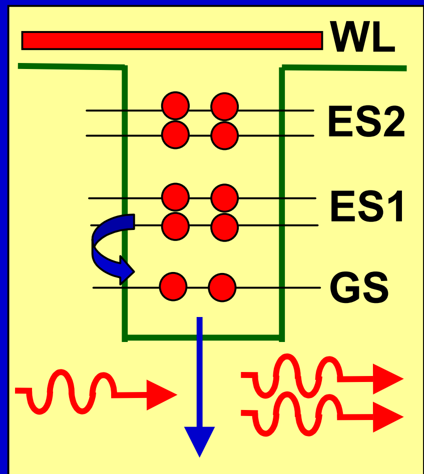
⇩

P_{sat}>19 dBm over 120 nm

Carrier reservoir

⇩

Large saturation power & fast recovery time



Polarisation sensitivity ? Preliminary evidence of polarisation control by shape engineering ***(Jayavel, APL 2004)***

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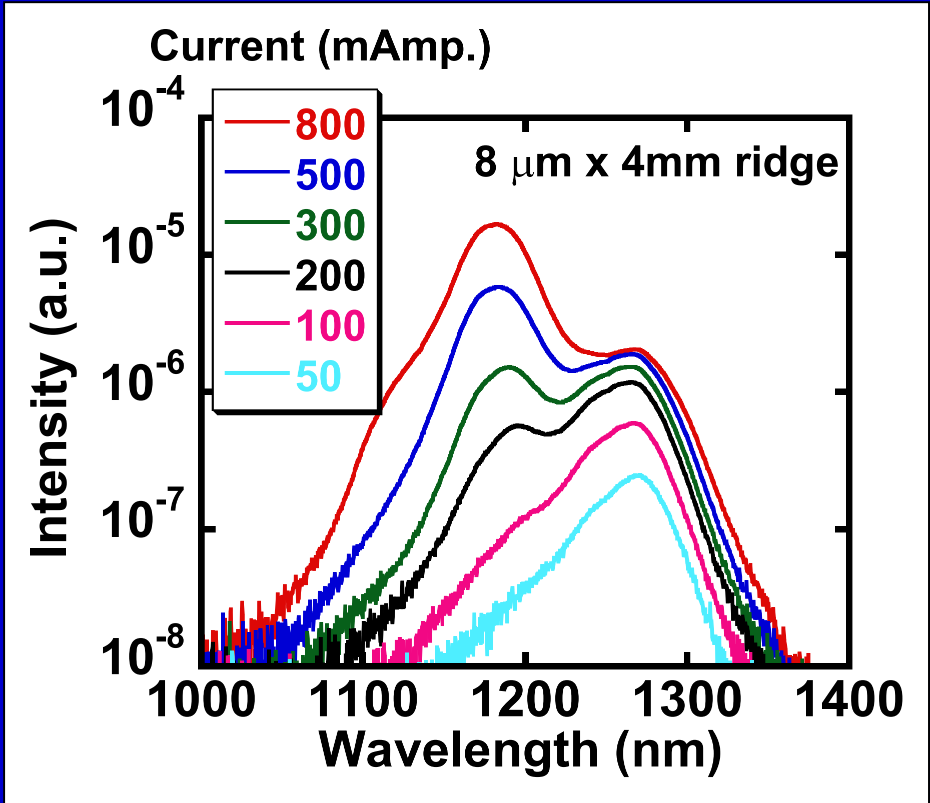
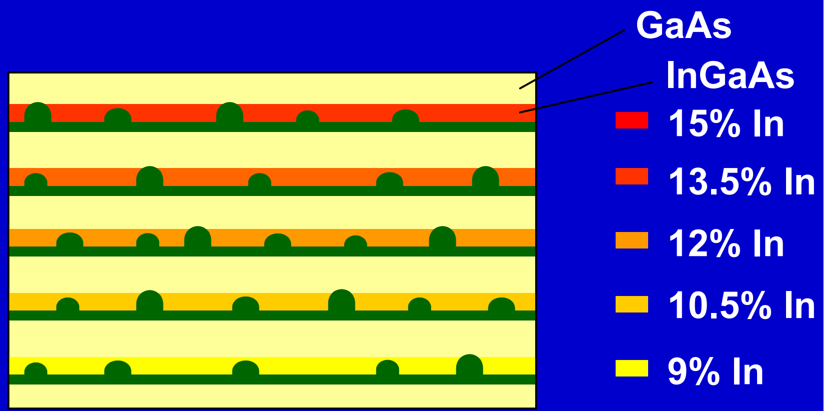
QD superluminescent diodes



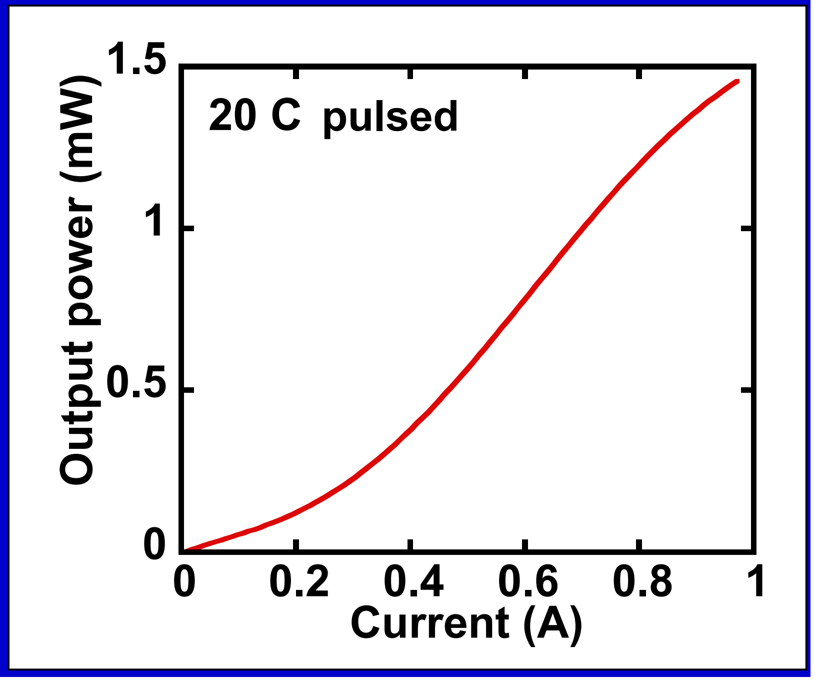
Chirped QD multilayers



GS: 55 nm FWHM

ES: 45 nm FWHM

GS + ES: > 100 nm



EPFL & EXALOS AG (Li et al, Electron. Lett. 2005)

QD lasers: Real applications coming up?

QD lasers are different, in some cases better

Low chirp
Feedback insensitivity
Large T_0

→ **Low-cost 10 Gb/s transmitters**

Broad gain → **SOAs, tunable lasers, SLDs**

ZIA quantum dot solutions

NSC NANOSEMICONDUCTOR

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