SAND2010-6137P

Physics underlying QD laser behaviors

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Lasers

Quantum optics

Experiment

Work was performed at Sandia's Solid-State Lighting Science Center, an Energy Frontier Research Center (EFRC) funded by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences.
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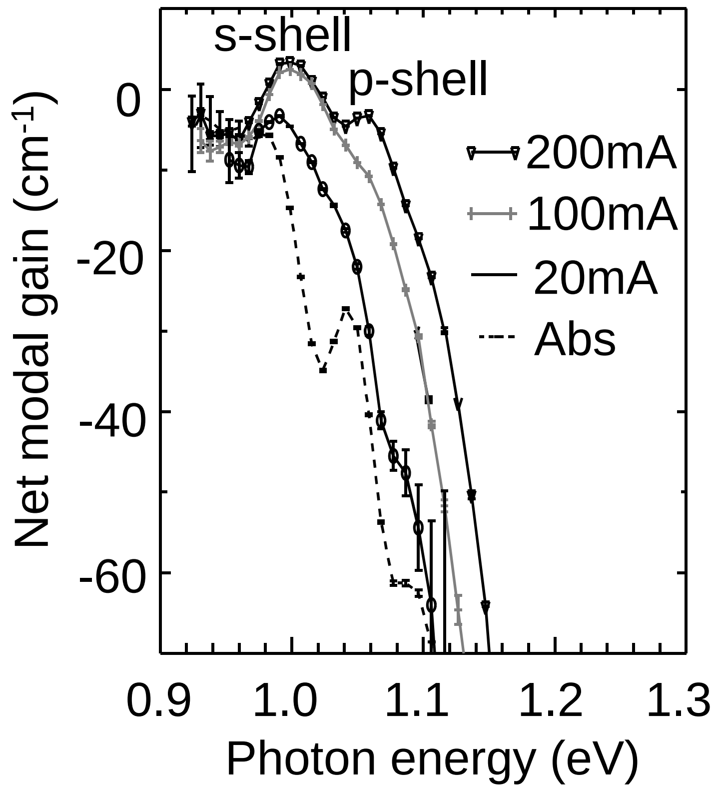
Quantum-dot absorption/gain spectra

Experiment

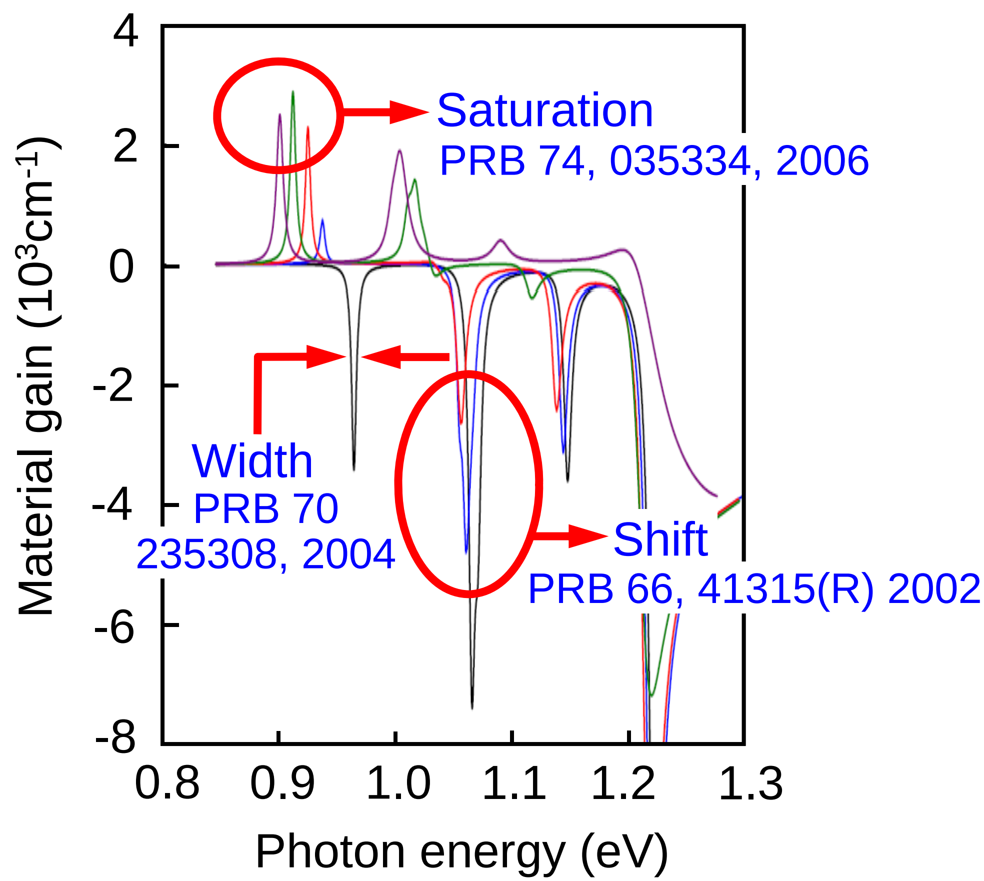
(Inhomogeneously broadened)



(measured at Cardiff University)

Calculation

(Intrinsic)

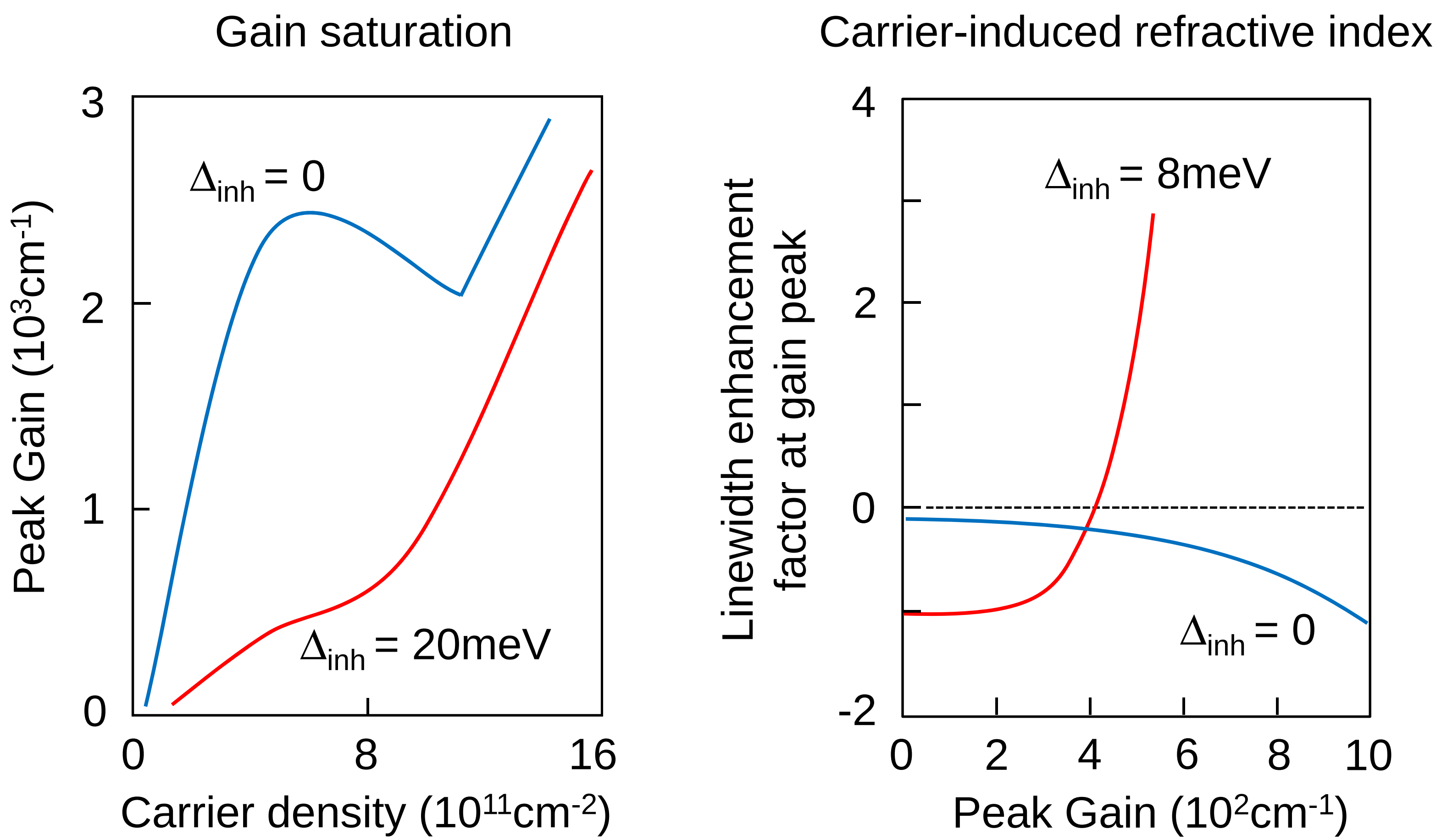


N_{dot}=2x10^{11}cm^{-2}, T=300K

N = 0.1x, 0.5x, 1x,2x,3x10^{12}cm^{-2}

Relevance to laser operation

InGaAs QD, 300K, $N_{dot}=5x10^{10}cm^{-2}$

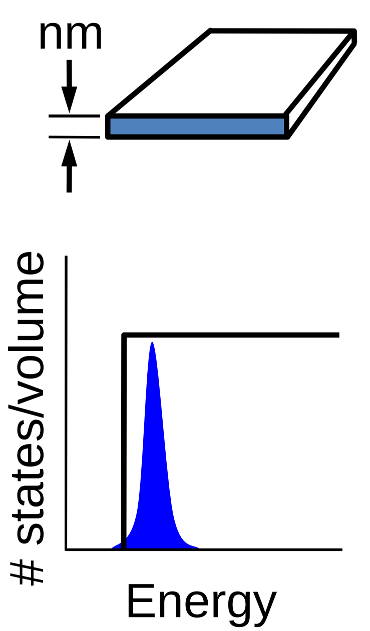


Underlying physics

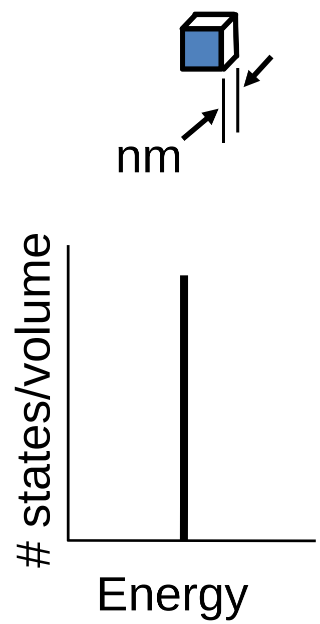
Free-Carrier effects

(Density of states)

Quantum well



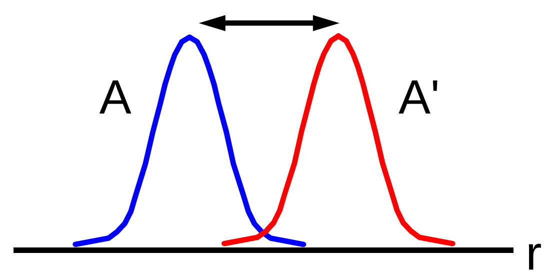
Quantum dot



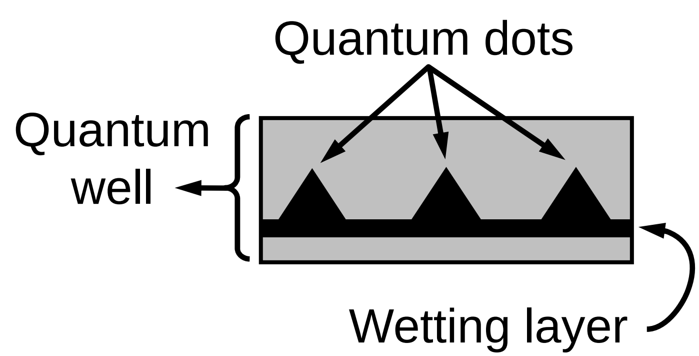
Many-body effects

(Quantum statistics + Coulomb interaction)

$$\{A, B\} = AB + BA \qquad \frac{e^2}{4\pi\varepsilon_0 r}$$



Active region



Strong influence from wells

Schneider, Chow, Koch, PRB **64**, 115315, 2001

Many-body effects

Hartree-Fock (mean field)

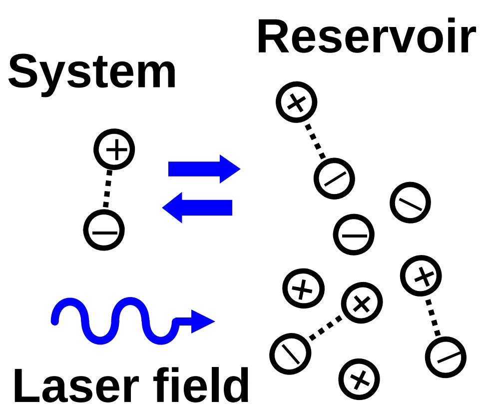
Bandgap renormalization

Exciton/Coulomb Enhancement

Correlations

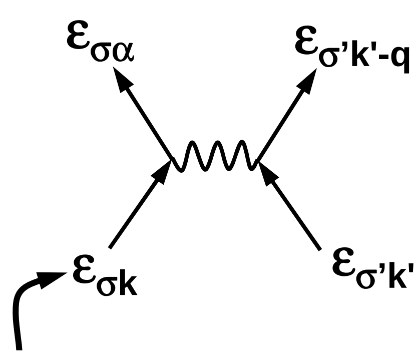
Relaxation, dephasing and screening

System is its own reservoir



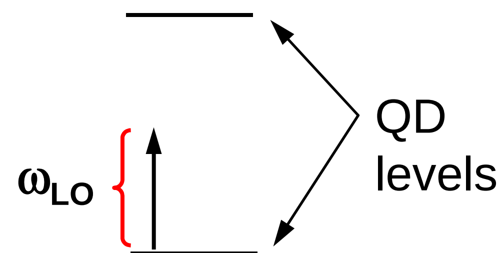
$$\frac{\partial p_k}{\partial t}\Big|_{col} = -\underbrace{\sigma^d_k p_k}_{\text{Diagonal}} + \underbrace{\sum_k \sigma^{nd}_{k,k'} p_{k'}}_{\text{Nondiagonal dephasing}}$$

Carrier-carrier scattering



Renormalized energies and memory

Polarons



Non perturbative carrier-phonon description for correct estimation of phonon bottleneck problem

Hamiltonian

$$H = \sum_n \varepsilon_n a_n^\dagger a_n + \sum_m \varepsilon_m b_m^\dagger b_m$$ *Single-particle*

$$- \sum_{n,m} \left(\mu_{nm} a_n^\dagger b_m^\dagger + \mu_{nm}^* b_m a_n\right) E(z,t)$$ *Light-matter*

$$+ \sum_{n,q} \hbar G_q a_{n+q}^\dagger a_n \left(b_q + b_{-q}^\dagger\right)$$ *Carrier - phonon*

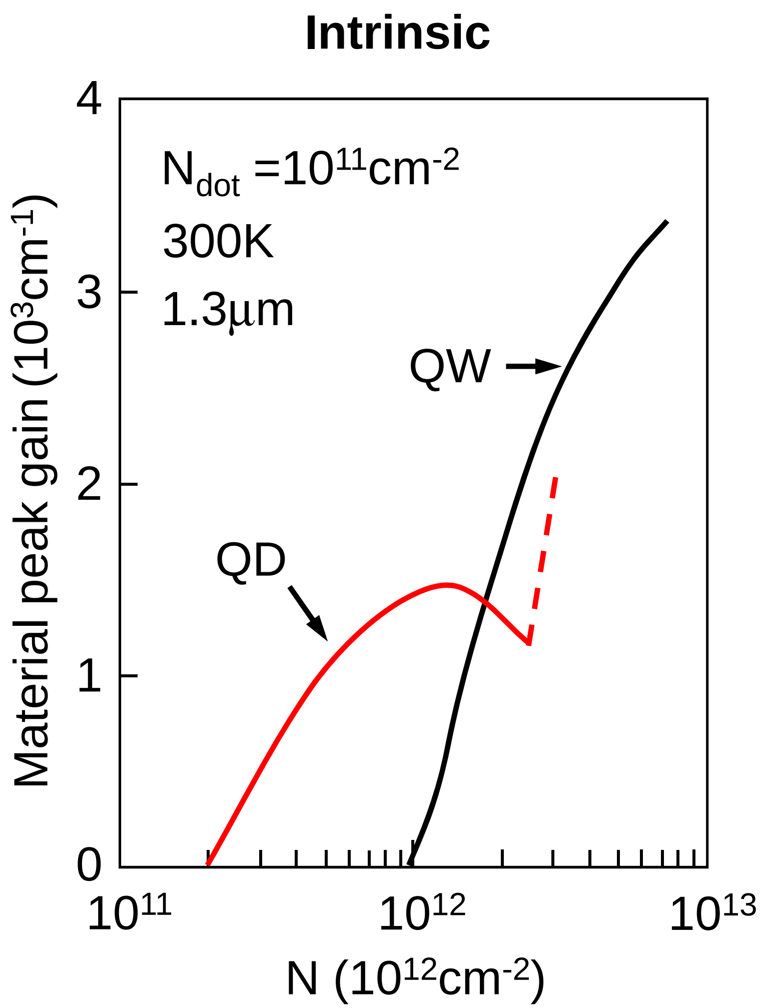
$$+ \frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} a_r^\dagger a_s^\dagger a_m a_n + \frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} b_r^\dagger b_s^\dagger b_m b_n - \sum_{n,m,r,s} W_{nm}^{rs} a_r^\dagger b_s^\dagger b_m a_n$$

Carrier – carrier

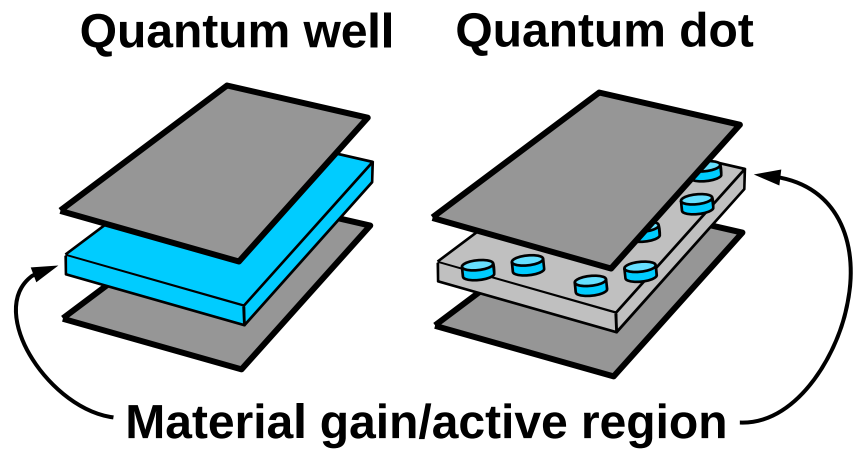
Fröhlich electron-LO phonon coupling

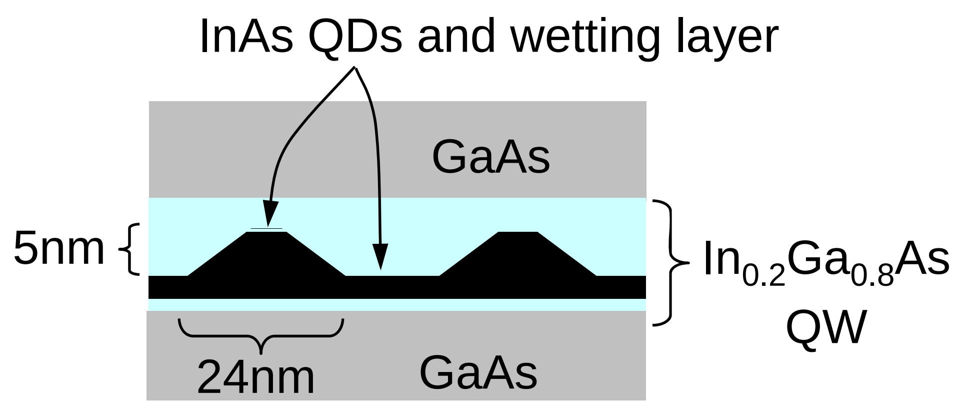
$$\int d^3r \, d^3r' \phi_r^*(r) \, \phi_s^*(r') \frac{e^2}{4\pi\varepsilon_b |r - r'|} \phi_m(r') \, \phi_n(r)$$

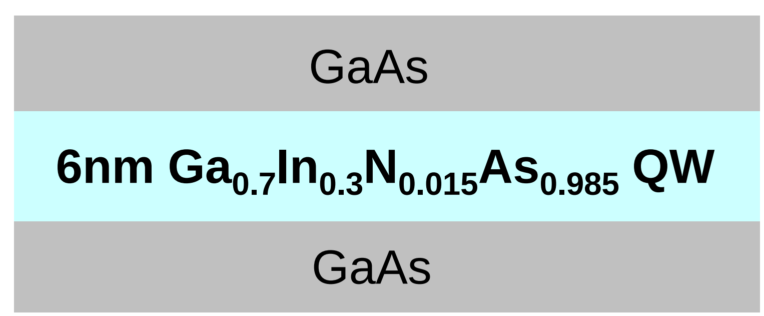
Quantum dot / quantum well comparison



Unambiguous scaling of the axii by eliminating dephasing rate as free parameter

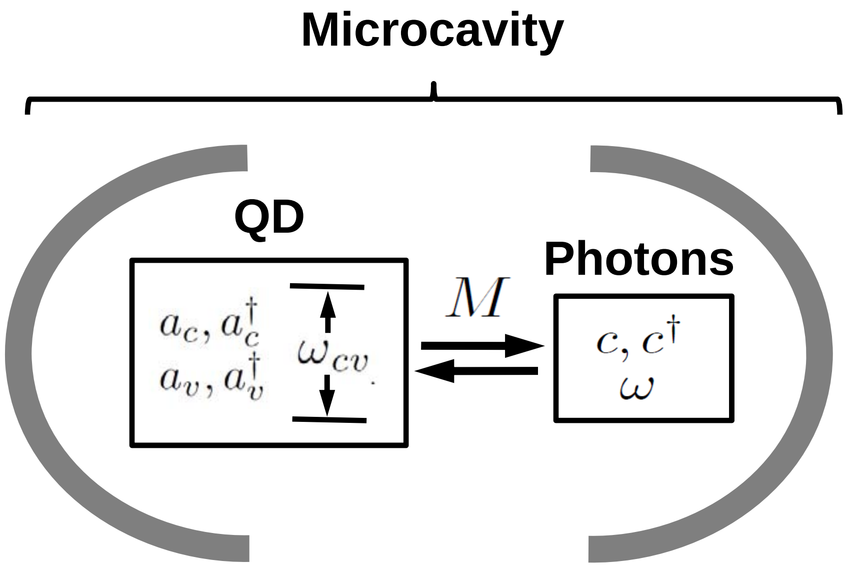






Quantum-dot cavity-quantum-electrodynamics (QD-CQED)

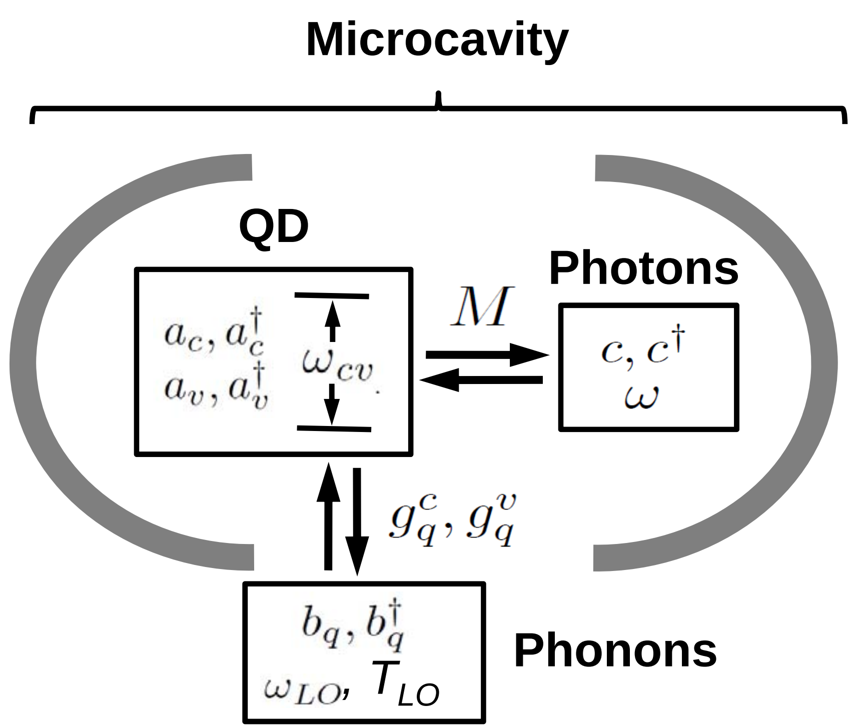
Single electron in quantum dot interacting with microcavity field



Control of spontaneous emission

Quantum-dot cavity-quantum-electrodynamics (QD-CQED)

Single electron in quantum dot interacting with microcavity field + phonon bath



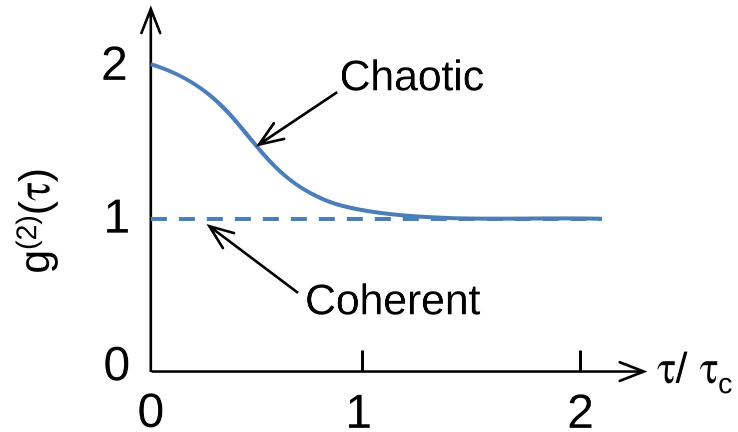
Control of spontaneous emission

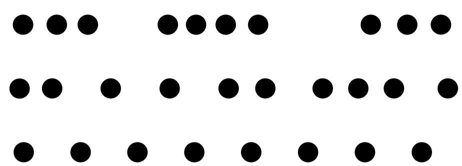
Modification of photon statistics

2nd-order correlation function

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

$$= \frac{\langle c^\dagger(t)\, c^\dagger(t+\tau)\, c(t+\tau)\, c(t)\rangle}{\langle c^\dagger(t)\, c(t)\rangle \langle c^\dagger(t+\tau)\, c(t+\tau)\rangle}$$



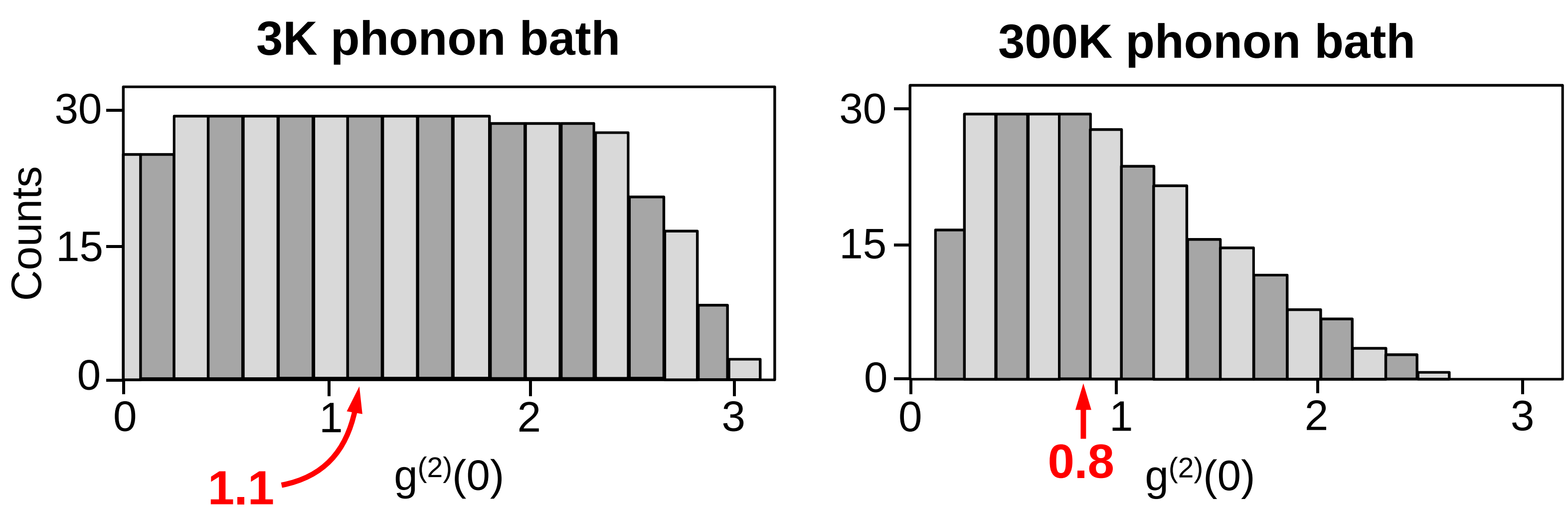


g (0) > 1 Bunched light

g (0) = 1 Coherent light (random)

g (0) < 1 Antibunched light

Start with thermal state



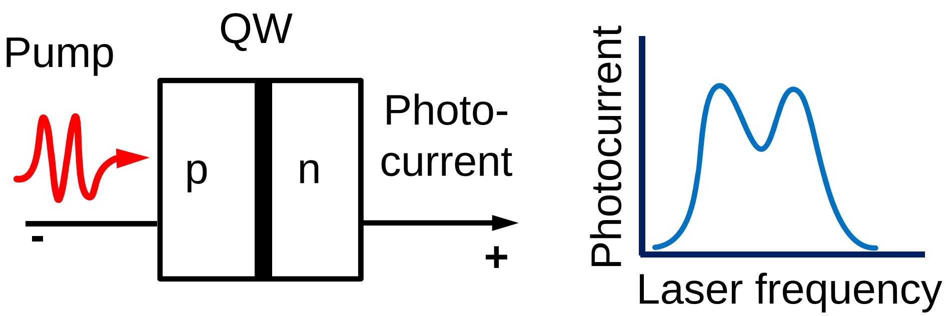
Carmele, Richter, Chow and Knorr, PRL **104**, 156801 (2010)

Experiments

First step is demonstration of strong light-matter interaction

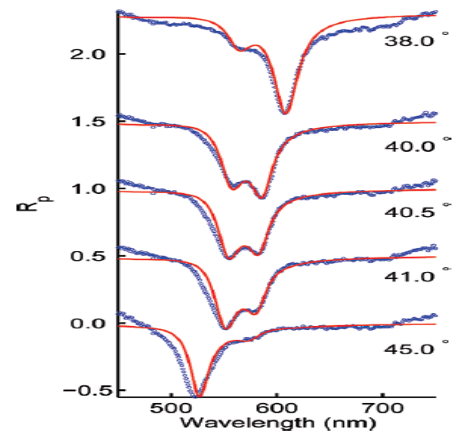
Optically pump

Early demonstrations



Reithmaier et al., Nature **432**, 197 (2004) and others

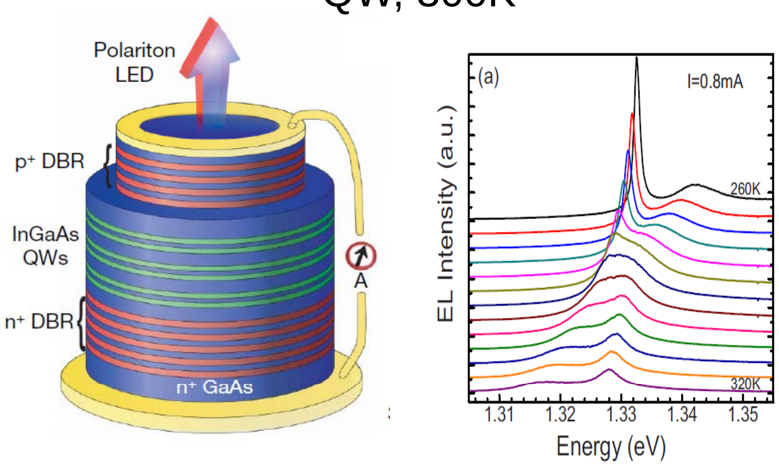
Plasmon mediated



Gomez et al., Nano Lett. **10**, 274 (2010)

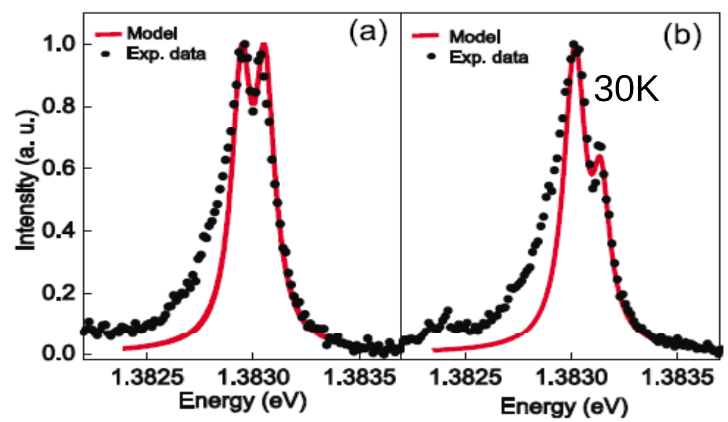
Electrically pump

QW, 300K



Tsintzos et al., Nature Lett. 453 373 (2008)
APL 94, 071109 (2009)

Quantum dots

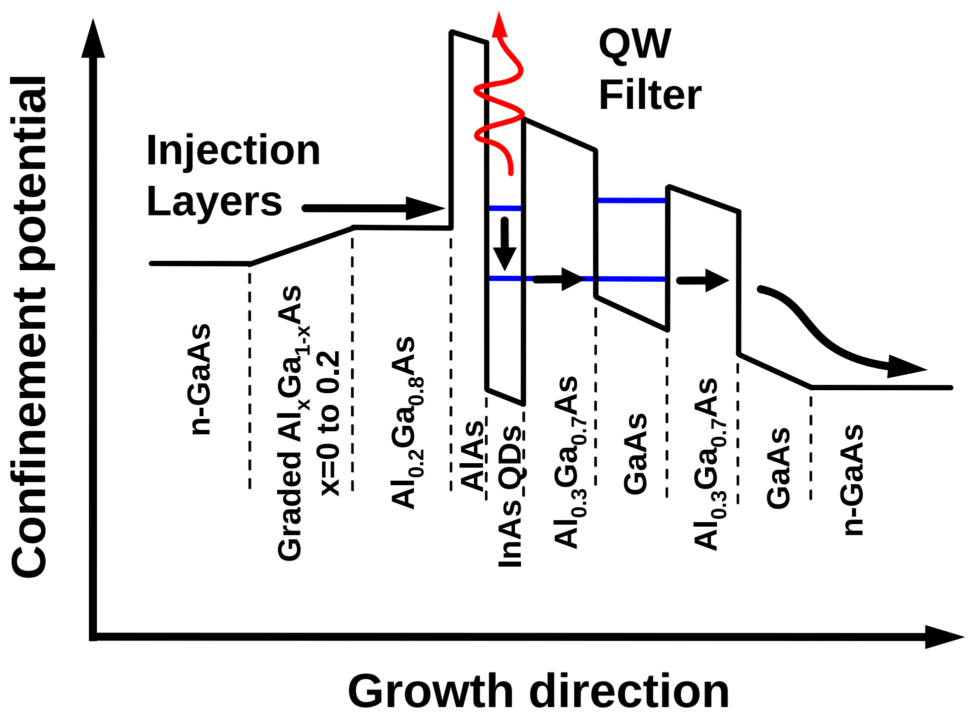


Kistner et al., APL 96, 221102 (2010)

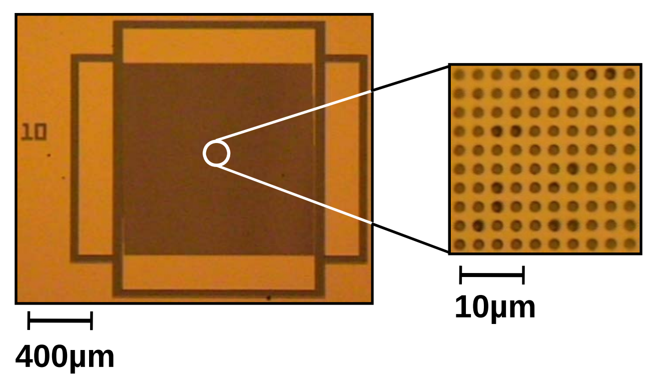
Experiments

Mid-IR emitter using inter-conduction-state transition in InAs quantum dots

(Sandia/U. Mass./Princeton)



Hole array and electrical contact



Observation of strong light-matter interaction in electrically-excited InAs quantum dots (Sandia/U. Mass./Princeton)

Rabi frequency

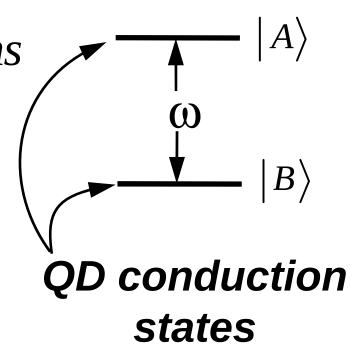
$e\times 10nm$ $\quad 3KV/cm$

$$\Omega_R = \frac{\wp E}{\hbar} \qquad 7\times10^{8}\ photons$$

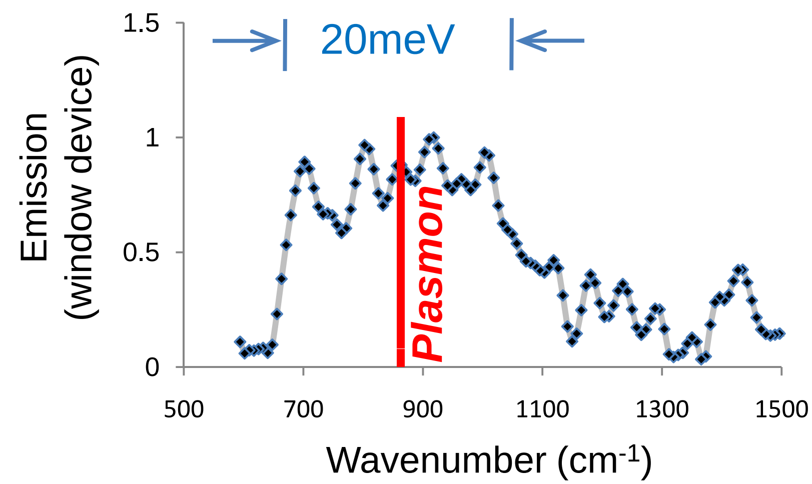
$$= 4.7\times10^{12}\, s^{-1}$$

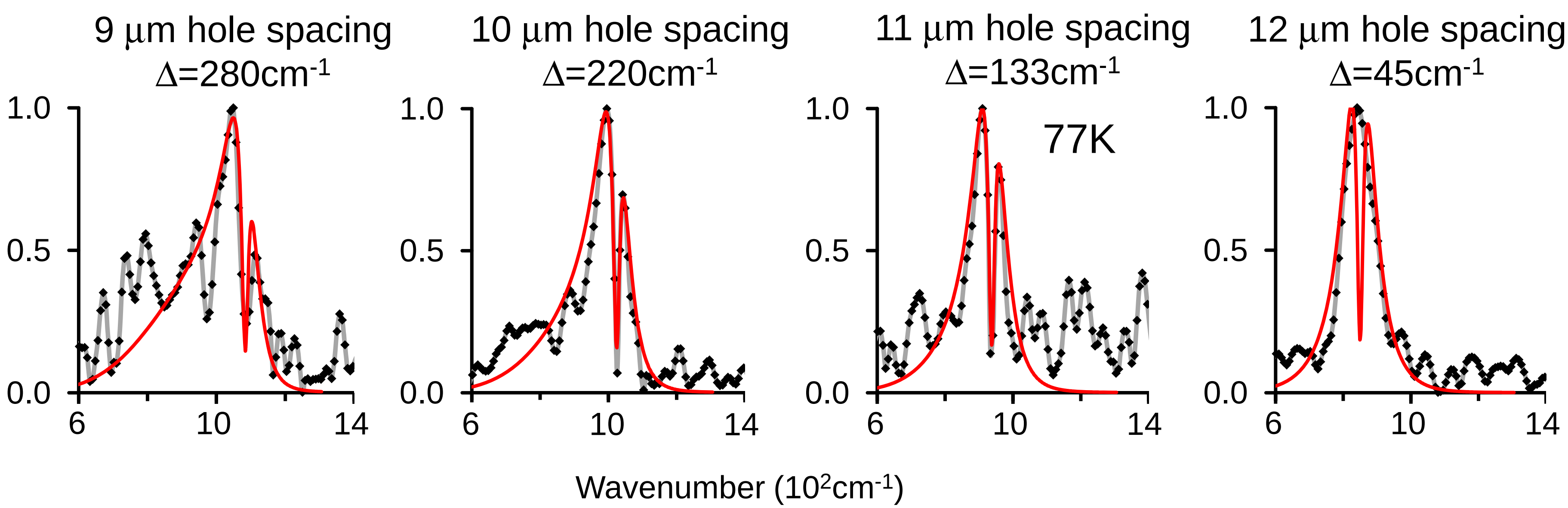
Dephasing

$$\gamma = 1.26\times10^{12}\, s^{-1}$$



Inhomogeneous broadening





Physics underlying QD laser behaviors

Lasers

Intrinsic laser properties determined by Coulomb correlations

Quantum optics

Control of photon statistics

Experiment

Strong light-matter interaction possible at high temperature
and with current injection

Collaborators

Lasers: Frank Jahnke and Michael Lorke (University of Bremen)

Quantum optics: Alexander Carmele and Andreas Knorr (Technical University, Berlin)

Experiment: Eric Shaner and Brandon Passmore (Sandia), Dan Wasserman (U. Massachusetts), Stephen Lyon (Princeton)