Lasers and quantum optics with quantum dots

SAND2010-5386P

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Quantum dot lasers

Quantum dot quantum optics

Experiment: Rabi splitting with electrically (incoherent) excitation

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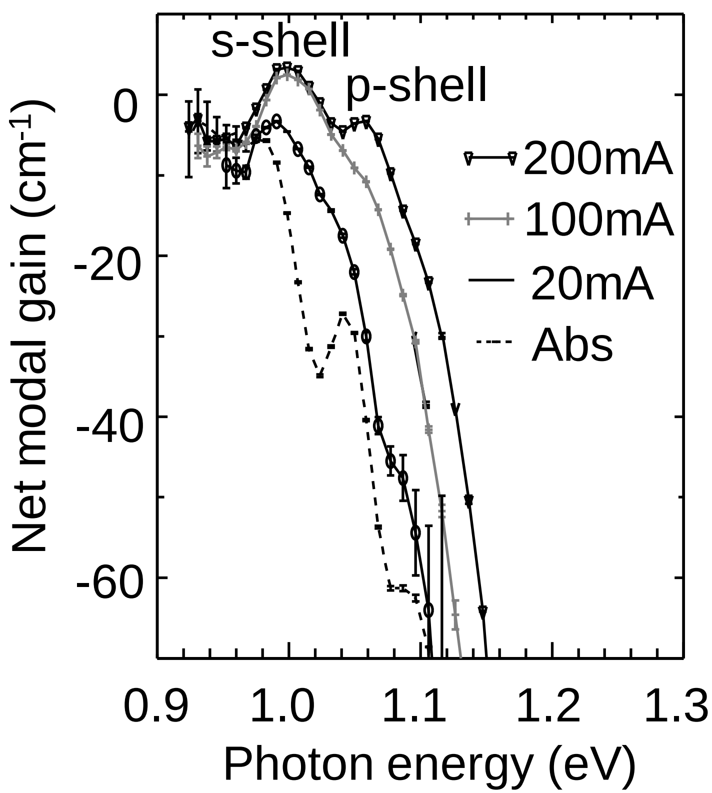
Sandia is operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy's National Security Administration under Contract DE-AC04-94AL85000.

Quantum-dot absorption/gain spectra

Experiment

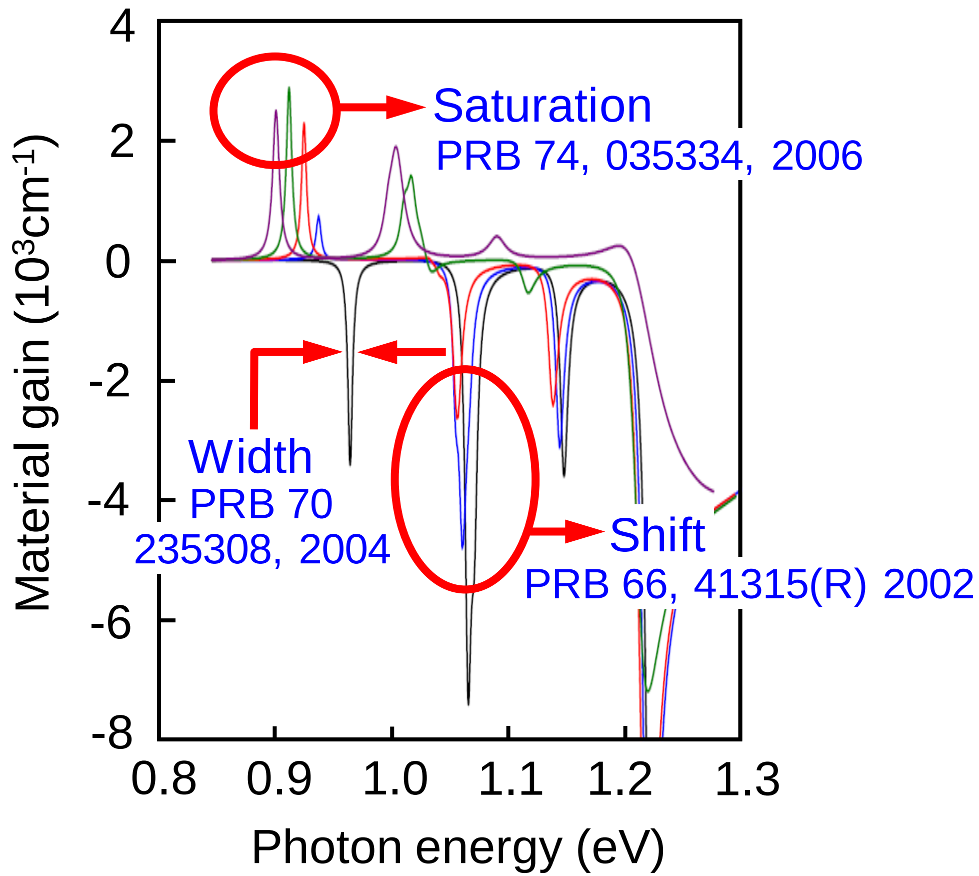
(Inhomogeneously broadened)



(measured at Cardiff University)

Calculation

(Intrinsic)

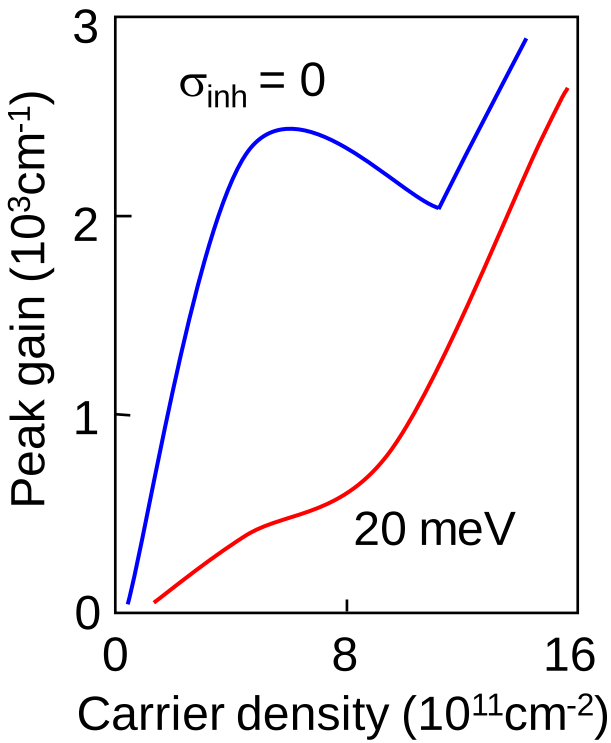


$N_{dot}=2x10^{11}cm^{-2}$, T=300K

N = 0.1x, 0.5x, 1x,2x,3x$10^{12}cm^{-2}$

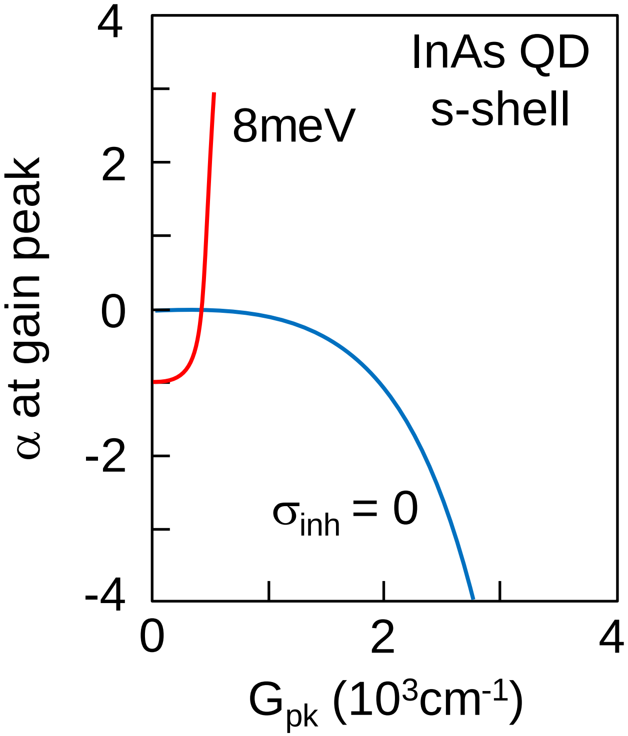
Relevance to laser operation

Gain saturation

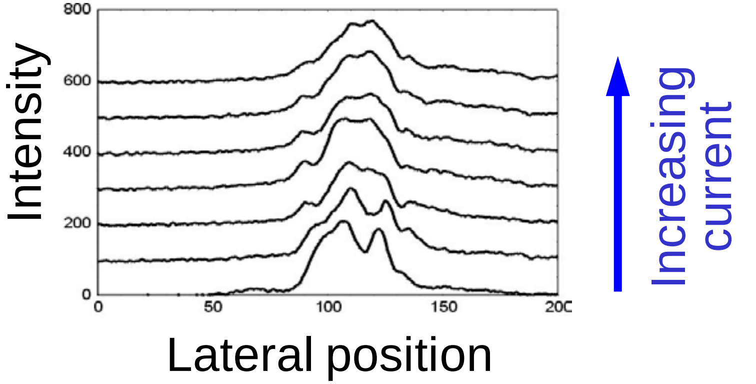


Lorke, Chow, Nielsen, Seebeck, Gartner, Jahnke, PRB **74**, 035334 (2006)

Carrier-induced refractive index



Expt: Reversed filamentation



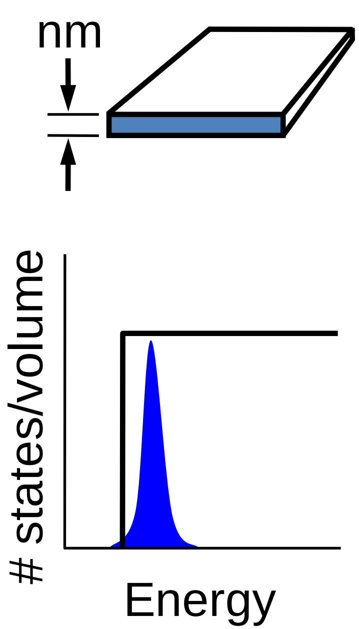
Smowton, et al, APL **81**, 3251, 2002

Underlying physics

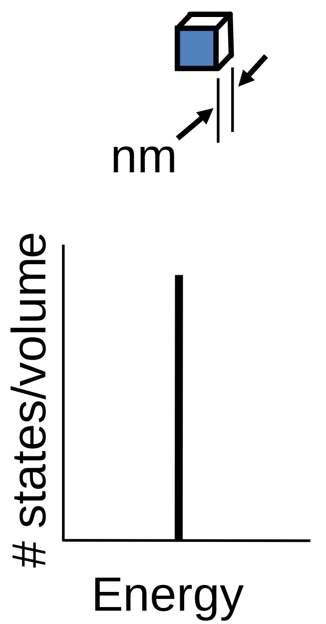
Free-Carrier effects

(Density of states)

Quantum well



Quantum dot

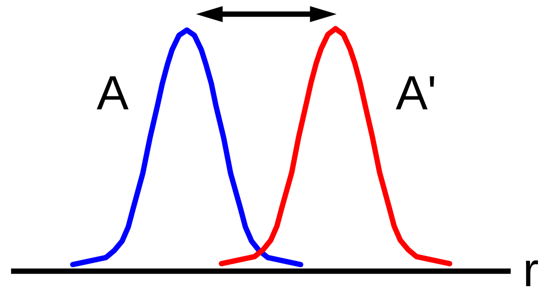


Many-body effects

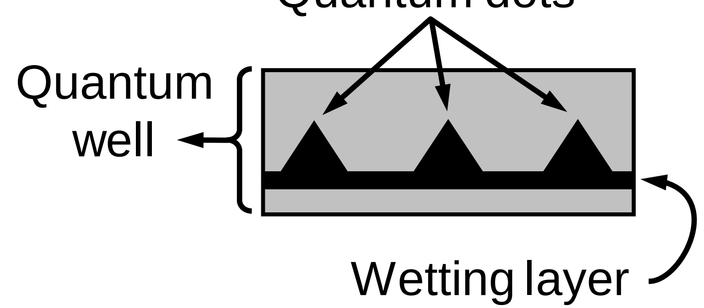
(Quantum statistics + Coulomb interaction)

$$\{A, B\} = AB + BA$$

$$\frac{e^2}{4\pi\varepsilon_0 r}$$



Active region



Strong influence from wells

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

Many-body effects

Hartree-Fock

Bandgap renormalization

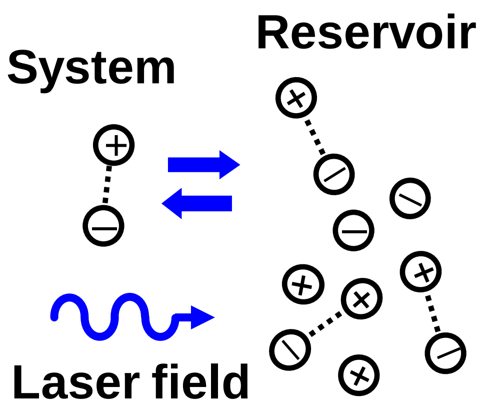
Exciton/Coulomb Enhancement

Correlations

Relaxation and dephasing

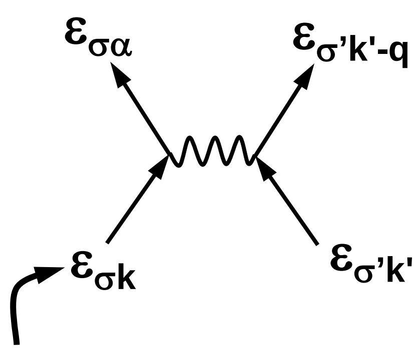
Screening

System is its own reservoir



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

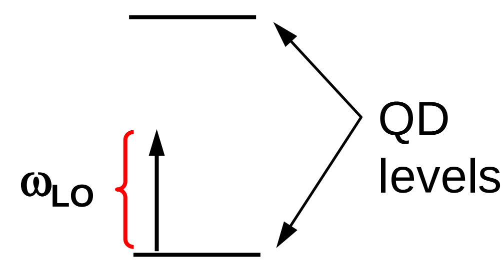
Carrier-carrier scattering



Renormalized energies

Memory effects

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*

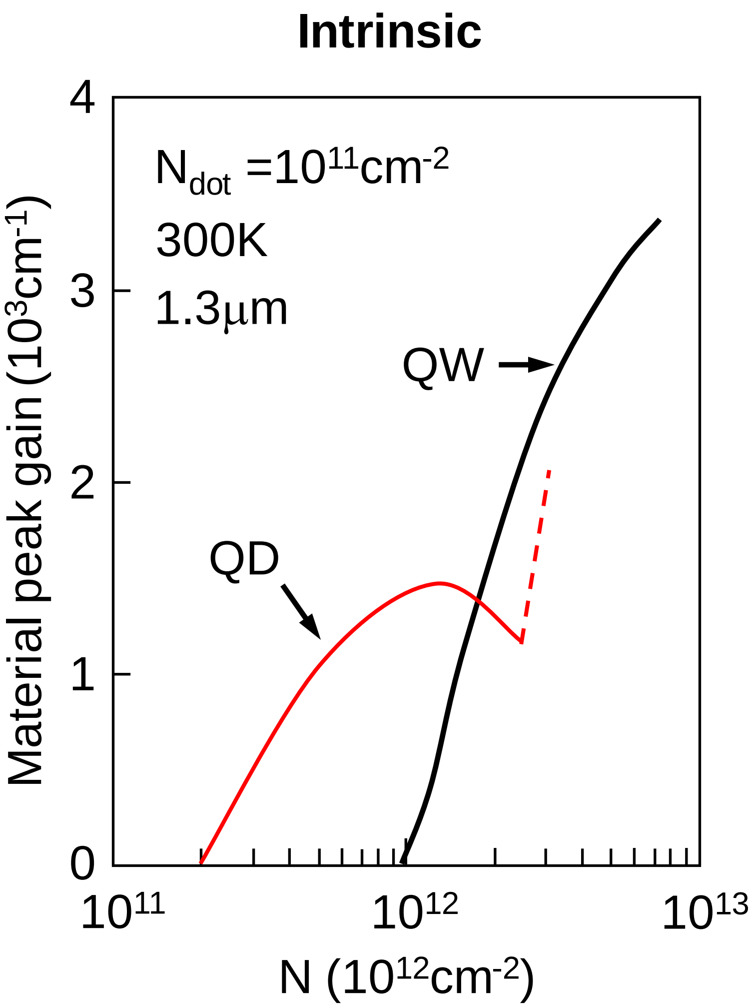
$$- \sum_{n,m} \left(\mu_{nm} a_n^\dagger b_m^\dagger + \mu_{nm}^* b_m a_n \right) E(z,t)$$ *Light-matter*

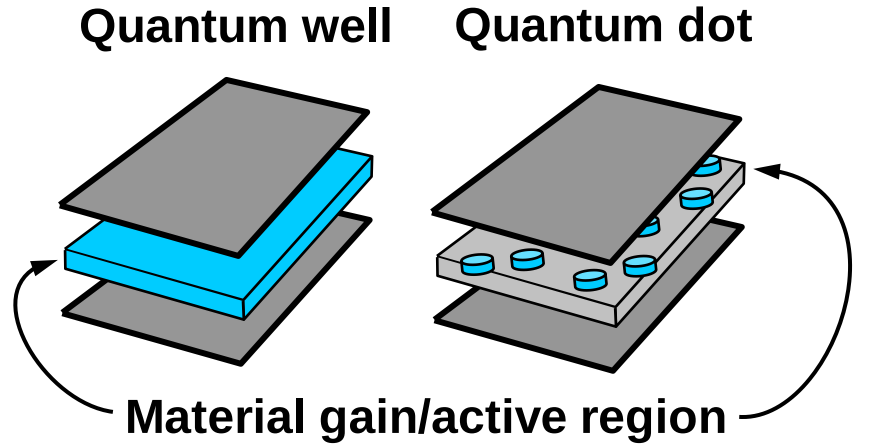
$$+ \sum_{n,q} \hbar G_q a_{n+q}^\dagger a_n \left(b_q + b_{-q}^\dagger \right)$$ *Carrier - phonon*

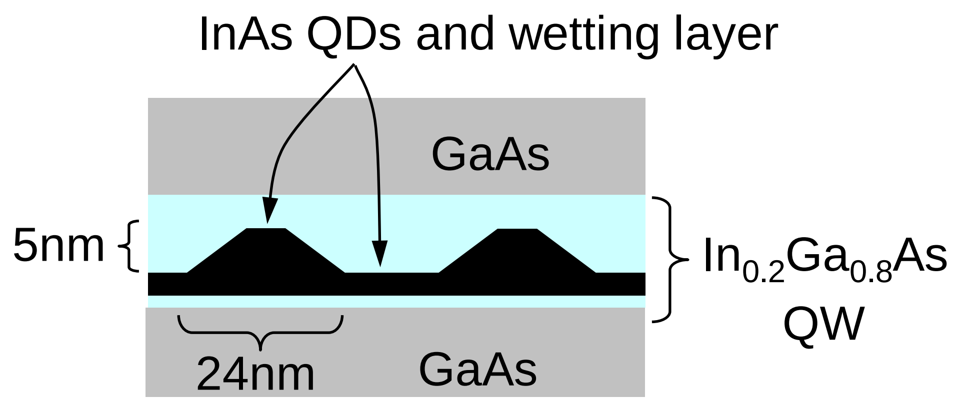
$$+ \frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} a_r^\dagger a_s^\dagger a_m a_n + \frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} b_r^\dagger b_s^\dagger b_m b_n - \sum_{n,m,r,s} W_{nm}^{rs} a_r^\dagger b_s^\dagger b_m a_n$$

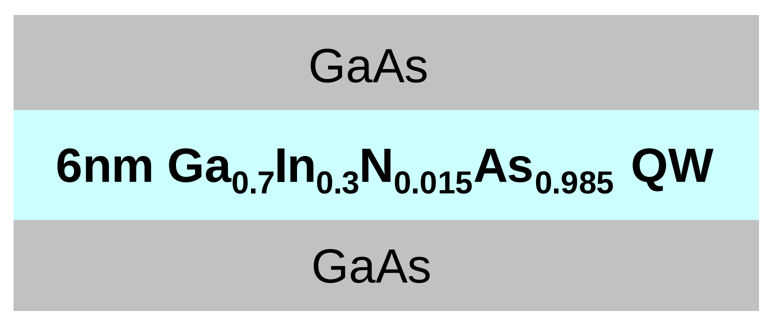
Carrier – carrier

Quantum dot / quantum well comparison

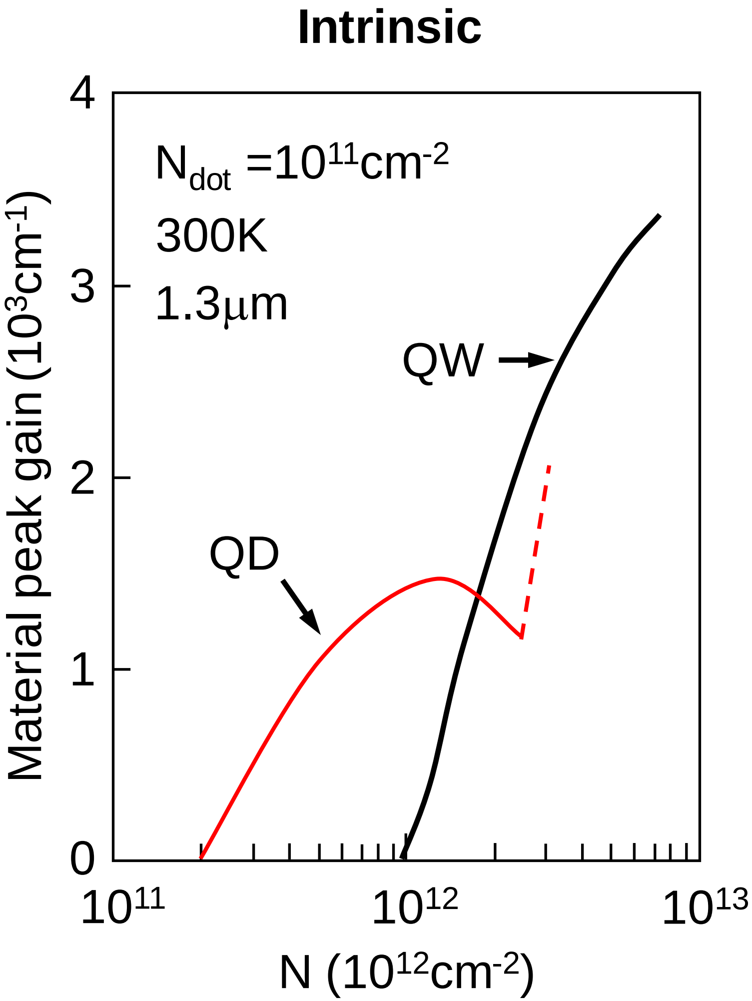


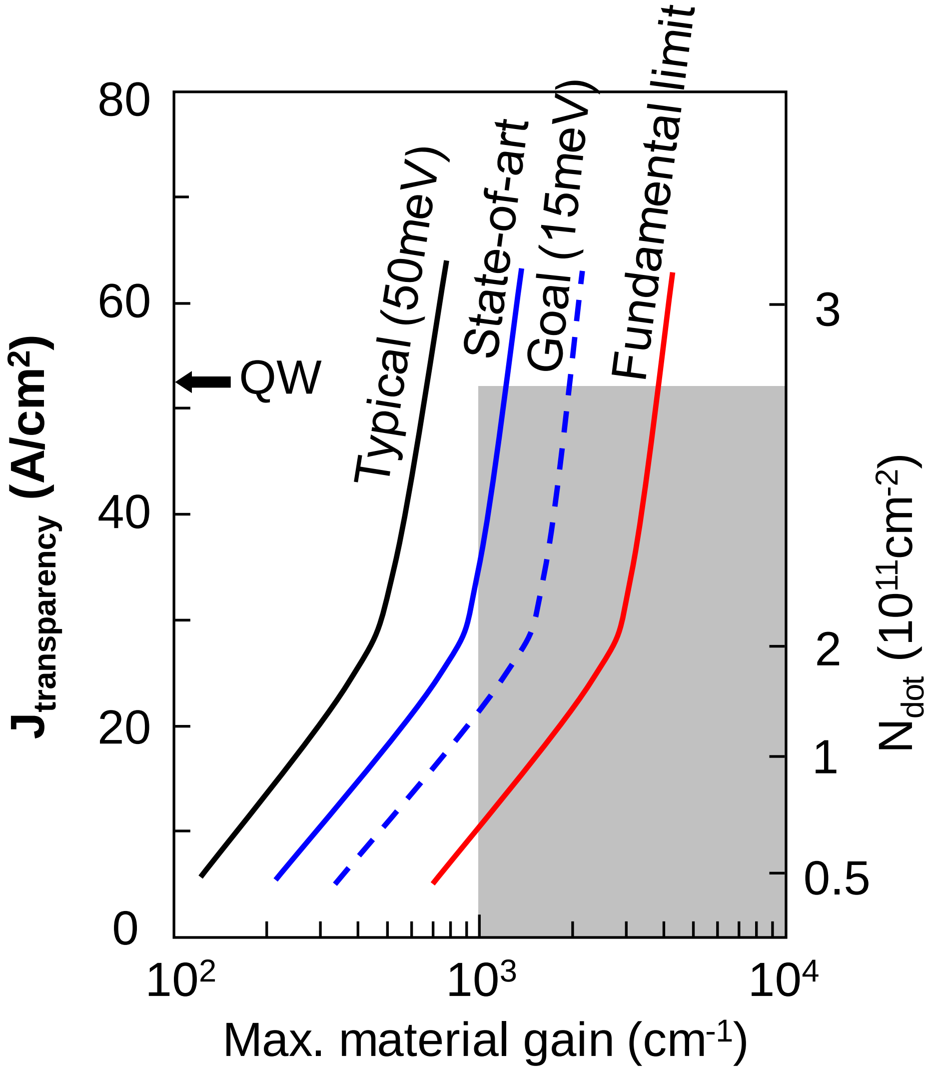






Quantum dot / quantum well comparison





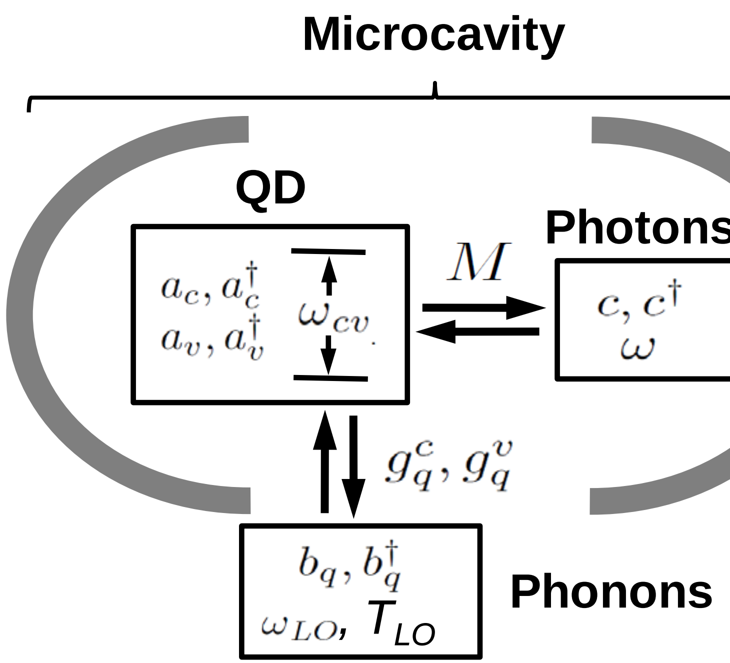
Unambiguous scaling of the axii by eliminating dephasing rate as free parameter

Curves show present status in relation to eventual performance and give guidance on where improvement can be effectively made

Quantum dots and quantum optics

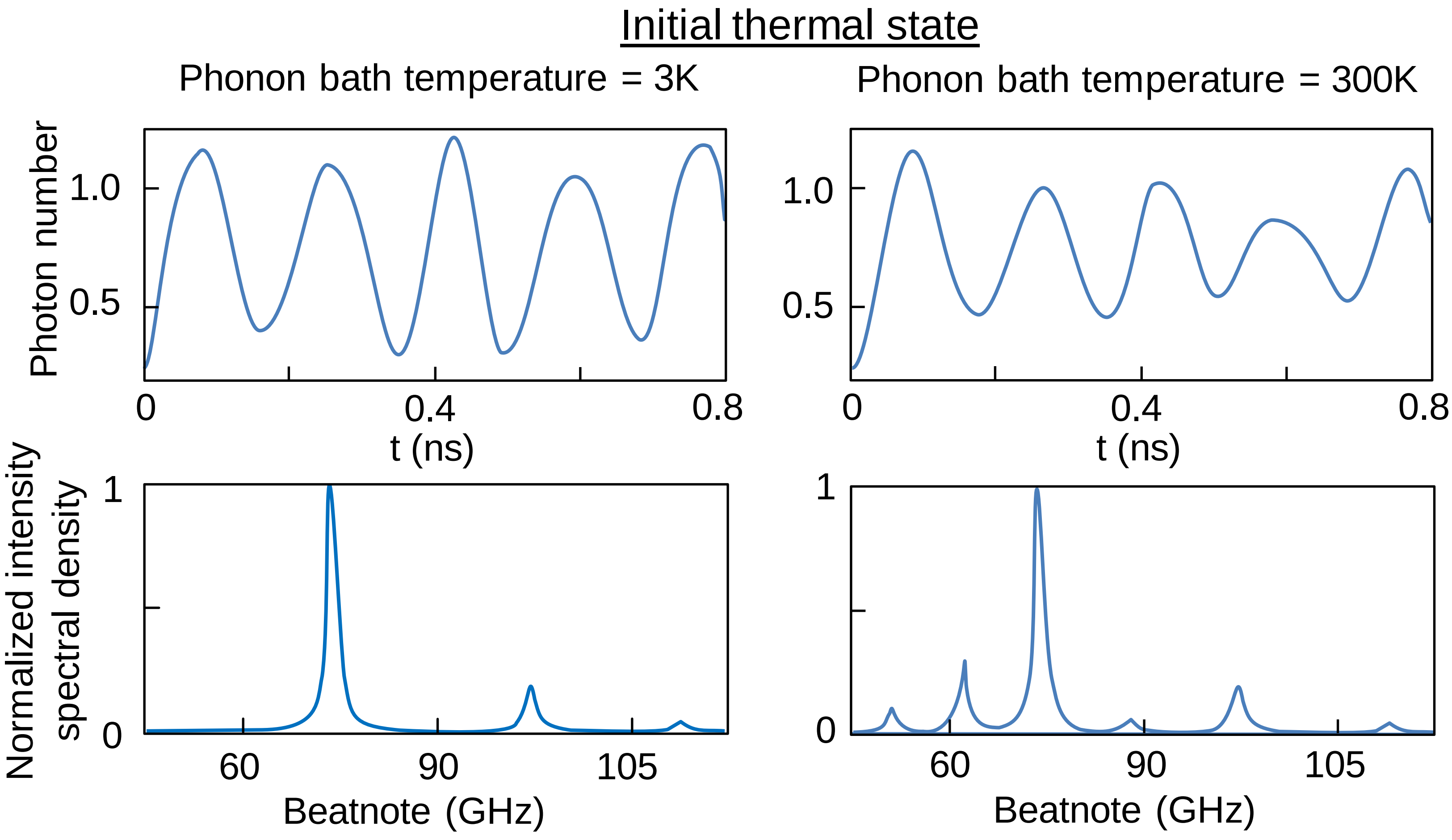
Single electron in quantum dot interacting with microcavity field + phonon bath

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



$$
\begin{aligned}
H = & \sum_{i=c,v} \hbar\omega_i a_i^\dagger a_i + \hbar\omega c^\dagger c - \hbar\omega_{LO} \sum_q a_q^\dagger a_q \\
& - \hbar M \left(a_v^\dagger a_c c^\dagger + h.a. \right) + \sum_{q,i=c,v} \left(\hbar g_q^i a_i^\dagger b_q + h.a. \right)
\end{aligned}
$$

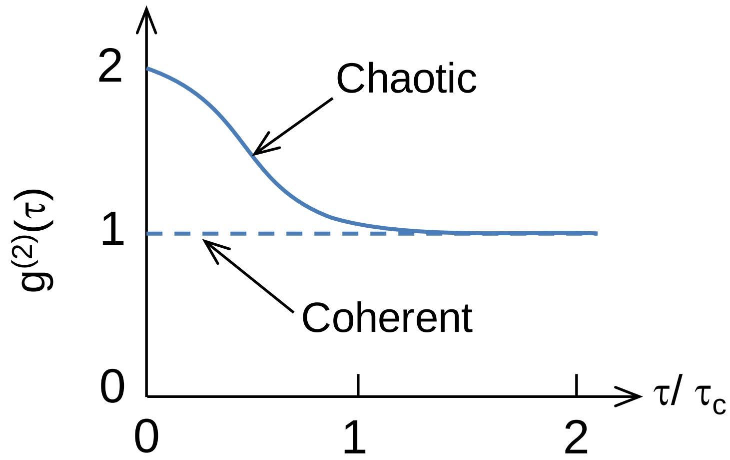
Same footing as light-matter

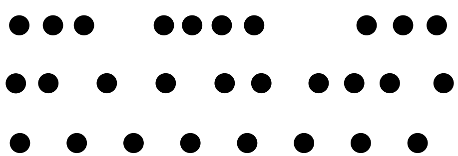

Initial thermal state
Phonon bath temperature = 3K
Phonon bath temperature = 300K
Photon number
1.0
0.5
0
0.4
0.8
t (ns)
Normalized intensity
spectral density
1
0
60
90
105
Beatnote (GHz)

2^{nd}-order correlation function

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

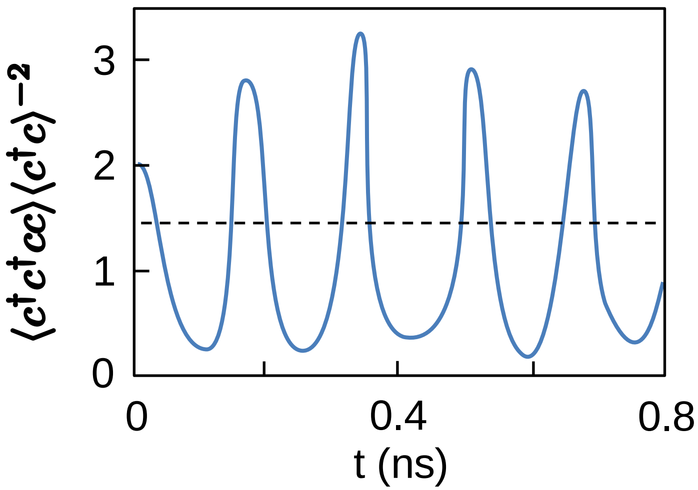
$$= \frac{\langle c^\dagger(t)\, c^\dagger(t+\tau)\, c(t+\tau)\, c(t)\rangle}{\langle c^\dagger(t)\, c(t)\rangle \langle c^\dagger(t+\tau)\, c(t+\tau)\rangle}$$

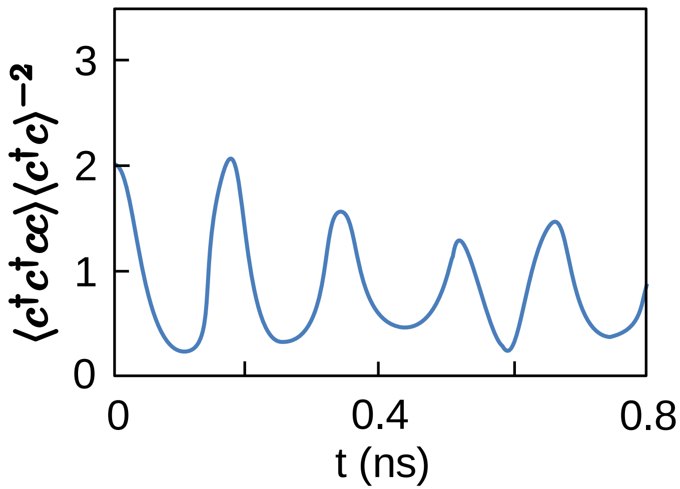




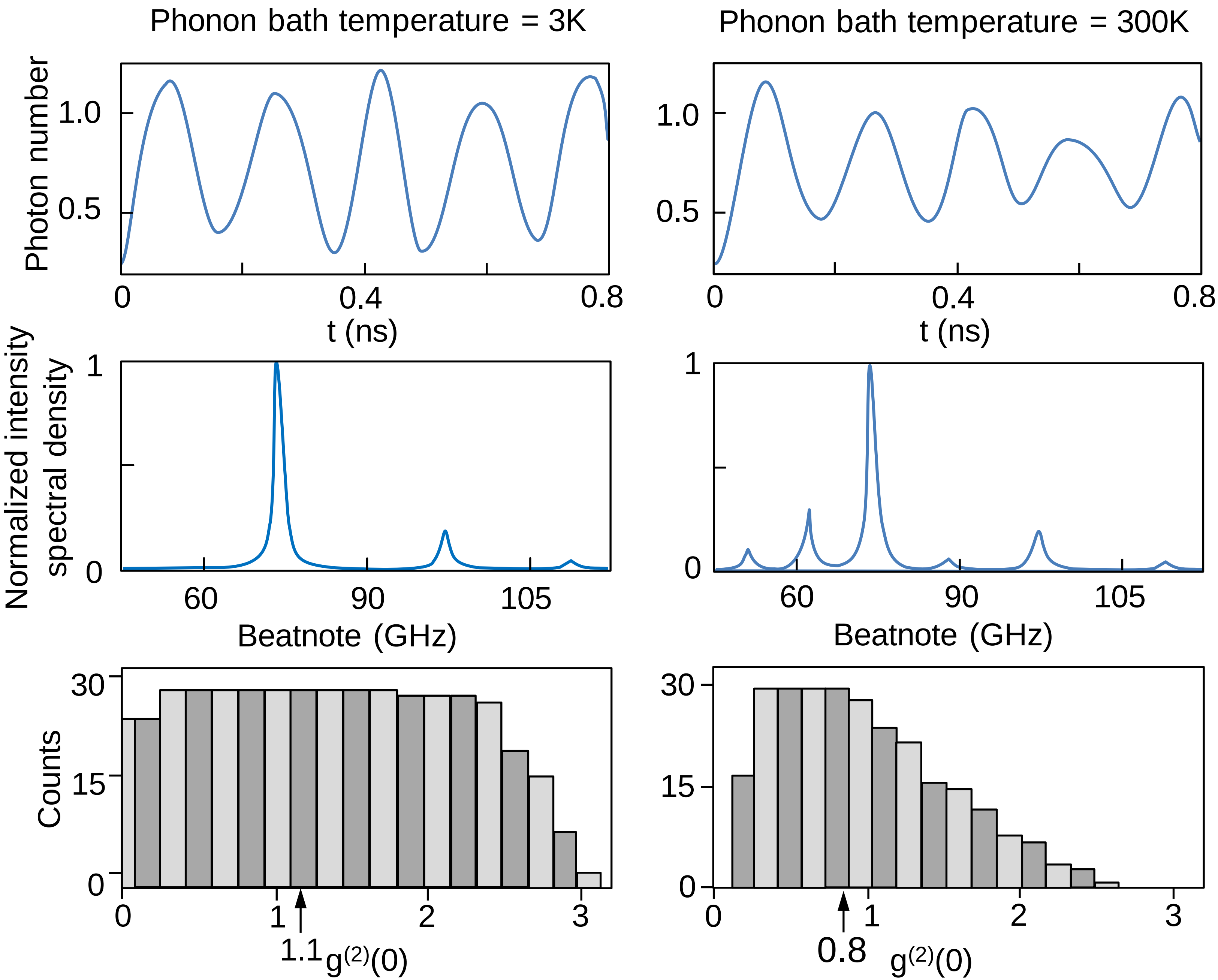
g (0) > 1 Bunched light
g (0) = 1 Coherent light (random)
g (0) < 1 Antibunched light

Thermal state





Initial thermal state



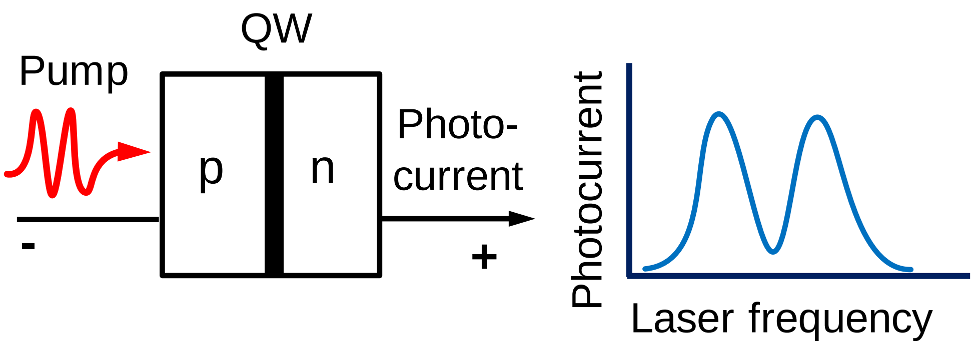
Carmele, Richter, Chow and Knorr, PRL **104**, 156801 (2010)

Experiments

Strong light-matter interaction in experiments

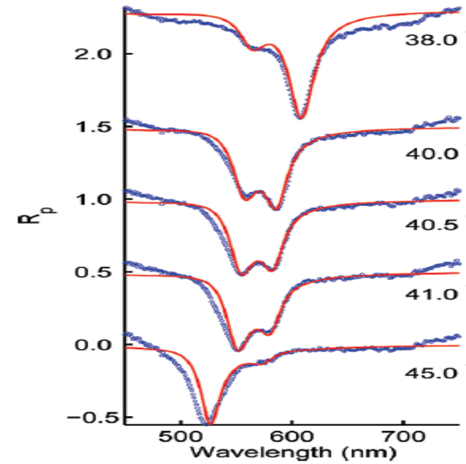
Optically pump

Early demonstrations



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

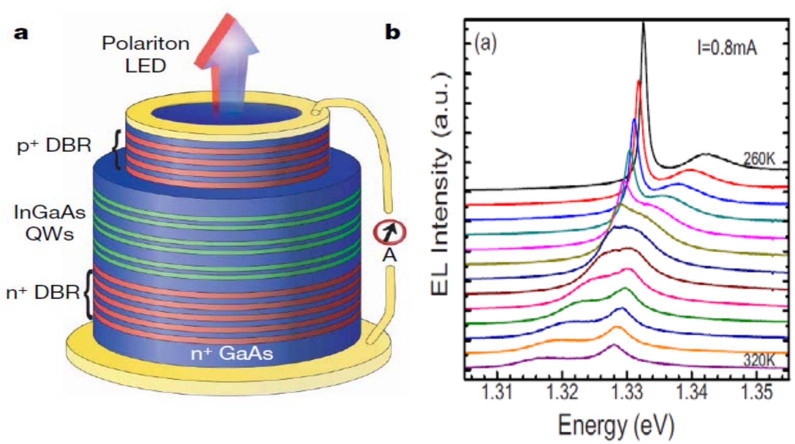
Plasmon mediated



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

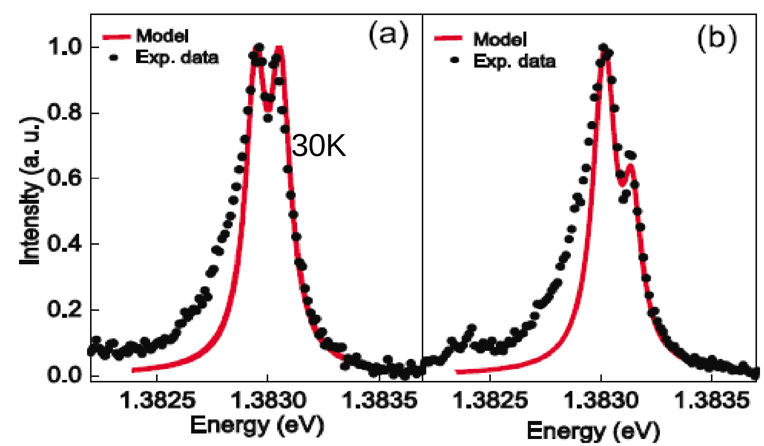
Electrically pump

QW, 300K



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

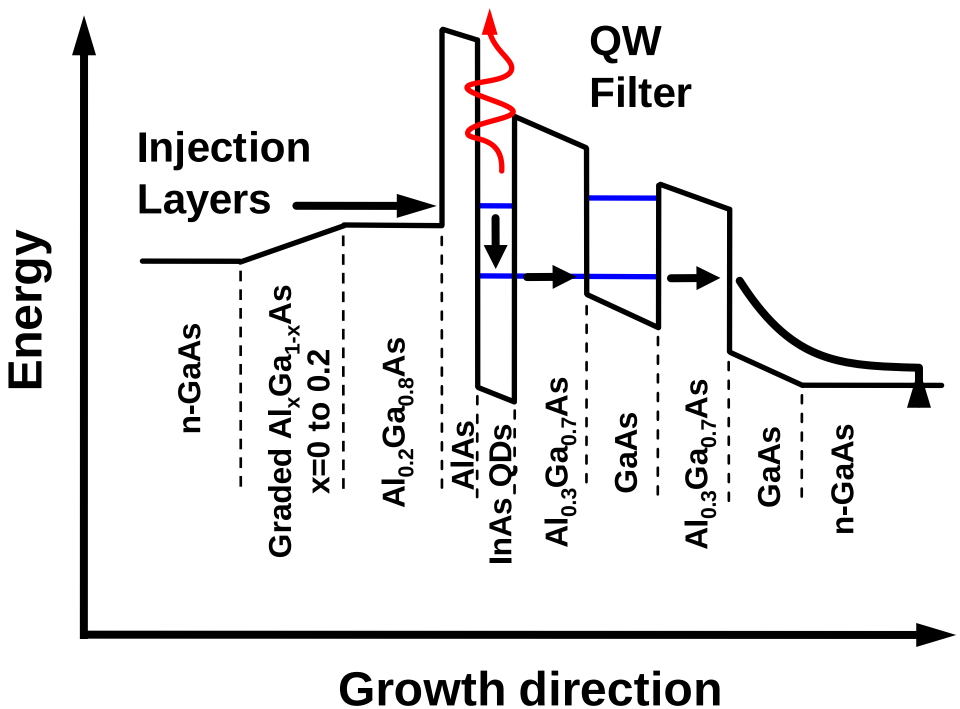
Quantum dots



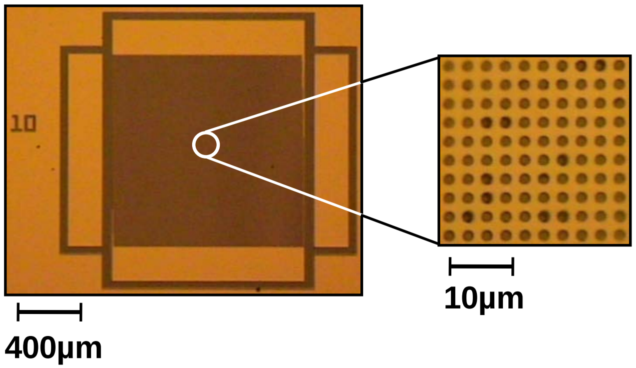
Kistner et al., APL 96, 221102 (2010)

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

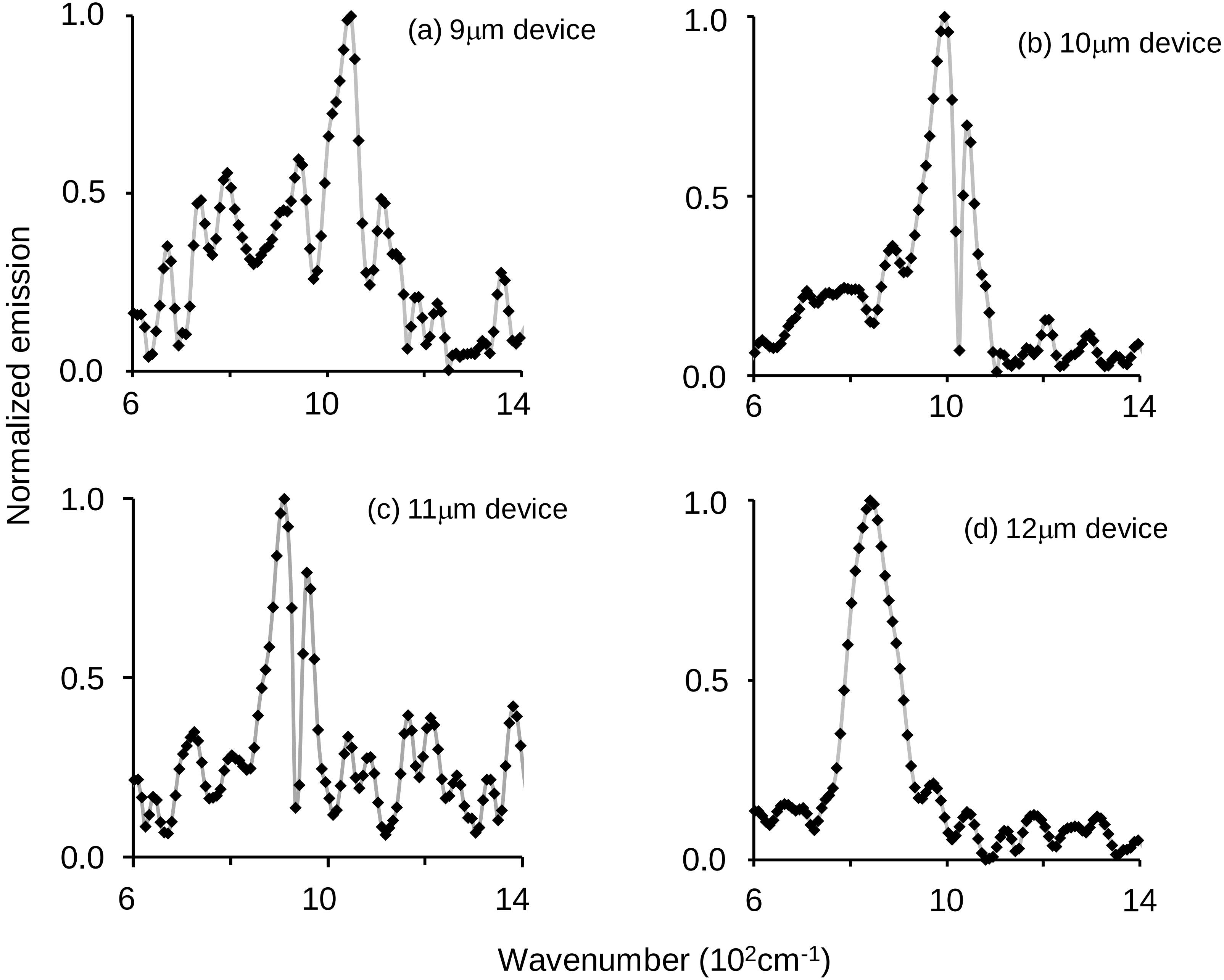
Confinement potential

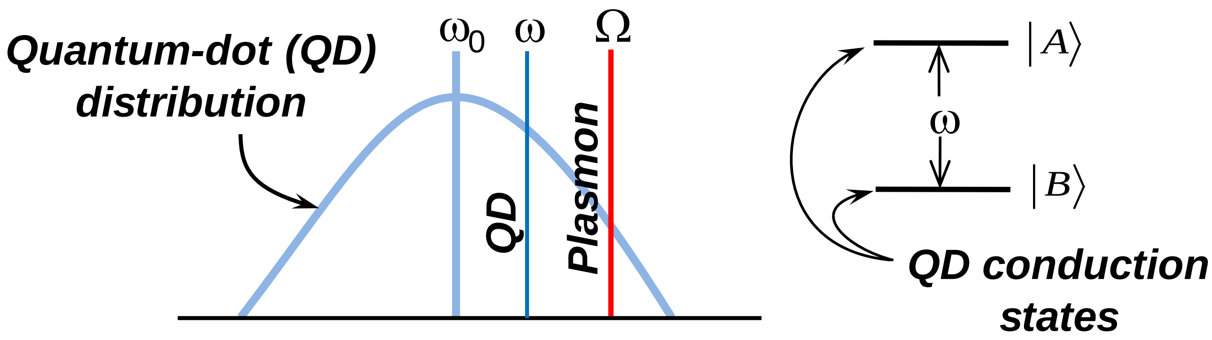


Hole array and electrical contact



Rabi flopping in an electrically-pumped device





Schrödinger Equation

$$i\hbar \frac{d}{dt}\left|\psi_\omega(t)\right\rangle = \left(H_0 + H_{QD-Plasmon} + H_{QD-photon}\right)\left|\psi_\omega(t)\right\rangle$$

Solve exactly

$$\sum_\omega \hbar\omega \left|a_\omega\right\rangle\left\langle a_\omega\right| + \sum_\nu \hbar\nu c_\nu^\dagger c_\nu$$

$$-E_p(t)\, u_p(z) \sum_\omega \mu\left(\left|a_\omega\right\rangle\left\langle b_\omega\right| + \left|b_\omega\right\rangle\left\langle a_\omega\right|\right)$$

Include to 1st order

$$-\sum_{\omega,\nu} u_\nu(z)\, \mu \sqrt{\frac{\hbar\nu}{A\varepsilon}}\left(\left|a_\omega\right\rangle\left\langle b_\omega\right| c_\nu + c_\nu^\dagger \left|b_\omega\right\rangle\left\langle a_\omega\right|\right)$$

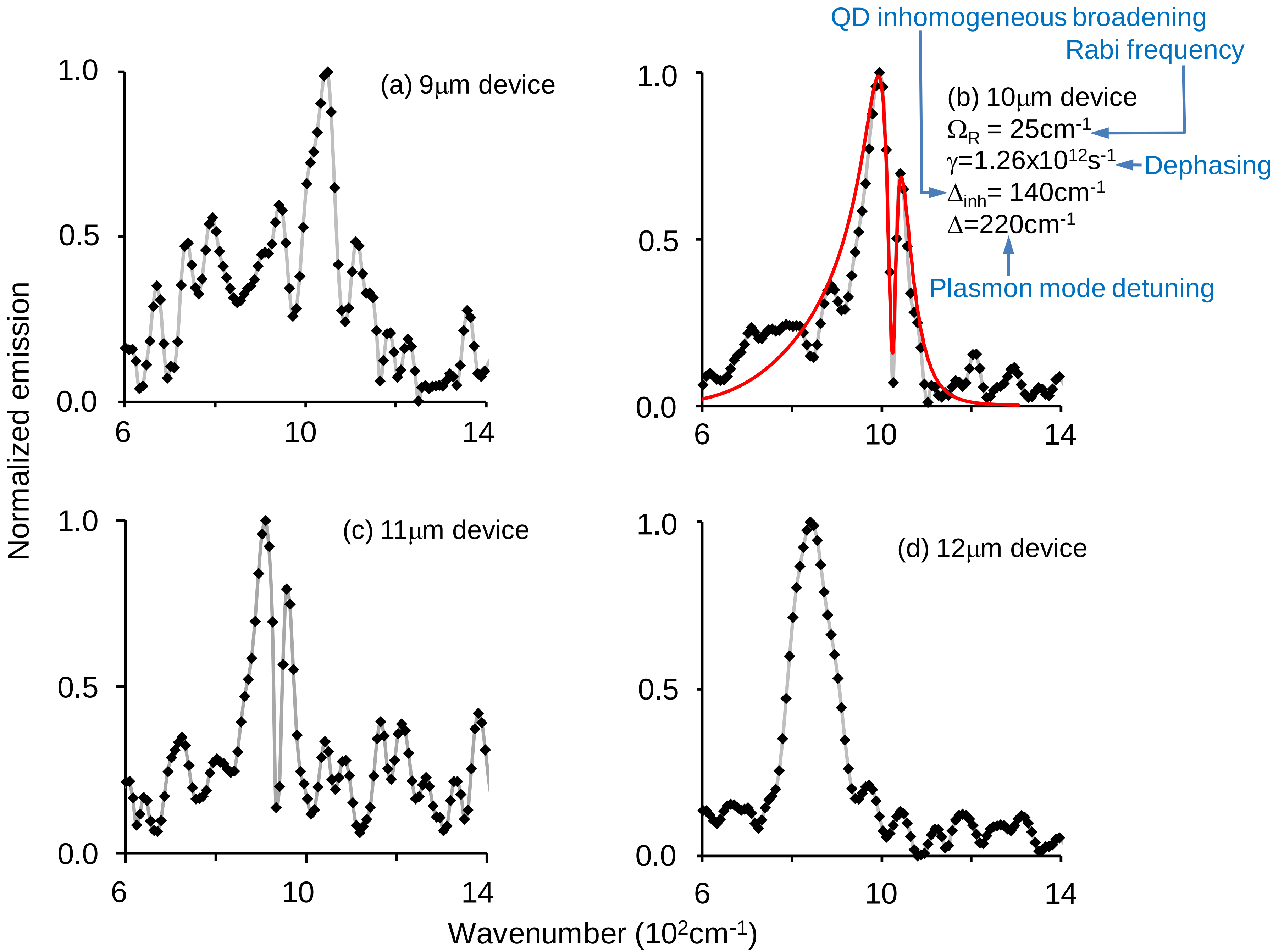
Intensity spectrum

$$S(\nu) = \int dt e^{i\nu t} \langle E(t+\tau) E(t) \rangle$$

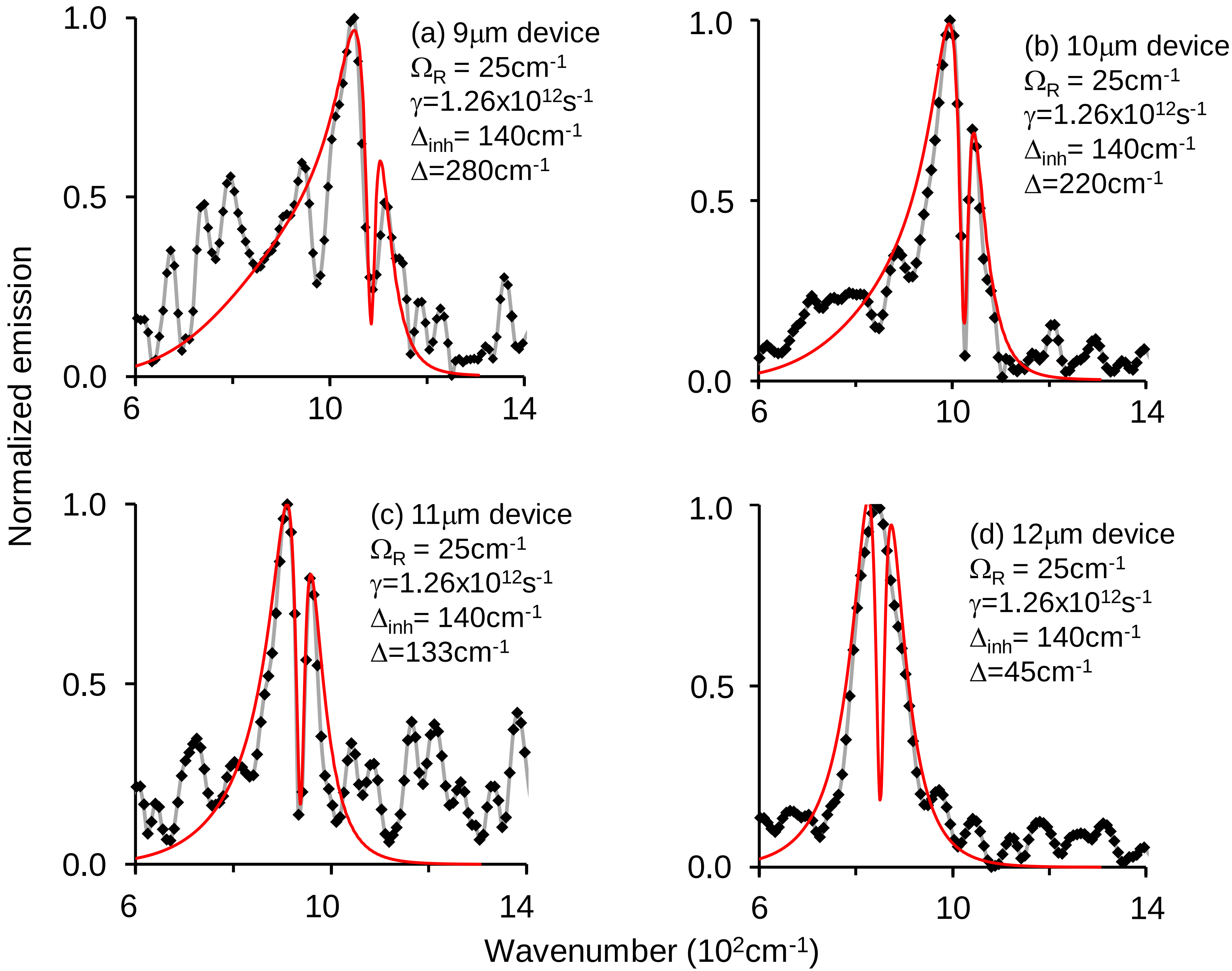
$$\frac{1}{T}\int_0^T dt \left\langle \psi_\omega(t+\tau) \middle| c_\omega^\dagger e^{iH\tau/\hbar} c_\omega \middle| \psi_\omega(t) \right\rangle$$

$$\int_0^\infty d\omega\, P(\omega) \left(\frac{g_\omega \Omega_R}{\Omega_R'}\right)^2 \gamma \left\{ \frac{\eta(\Omega_R')}{\gamma + i(2\upsilon - \Omega - \omega + \Omega_R')} + \frac{\eta(-\Omega_R')}{\gamma + i(2\upsilon - \Omega - \omega + \Omega_R')} \right\} + c.c.$$

$$\eta(\Omega_R') = \frac{1}{\gamma^2 + (\Delta - \Omega_R')^2} - \frac{1}{[\gamma - i(\Delta - \Omega_R')][\gamma + i(\Delta + \Omega_R')][\gamma + i\Omega_R']}$$



Normalized emission
(a) 9μm device
(b) 10μm device
Ω_R = 25cm-1
γ=1.26x10^12 s-1
Δ_inh= 140cm-1
Δ=220cm-1
QD inhomogeneous broadening
Rabi frequency
Dephasing
Plasmon mode detuning
(c) 11μm device
(d) 12μm device
1.0
0.5
0.0
6
10
14
Wavenumber (10^2 cm-1)



(a) 9μm device
Ω_R = 25cm-1
γ=1.26x10^12s-1
Δ_inh= 140cm-1
Δ=280cm-1
(b) 10μm device
Ω_R = 25cm-1
γ=1.26x10^12s-1
Δ_inh= 140cm-1
Δ=220cm-1
(c) 11μm device
Ω_R = 25cm-1
γ=1.26x10^12s-1
Δ_inh= 140cm-1
Δ=133cm-1
(d) 12μm device
Ω_R = 25cm-1
γ=1.26x10^12s-1
Δ_inh= 140cm-1
Δ=45cm-1
Normalized emission
Wavenumber (10^2cm-1)
1.0
0.5
0.0
6
10
14

Input parameters

Inter-conduction-level

$e \times 10nm$

$3KV/cm$

$7 \times 10^8\ photons$

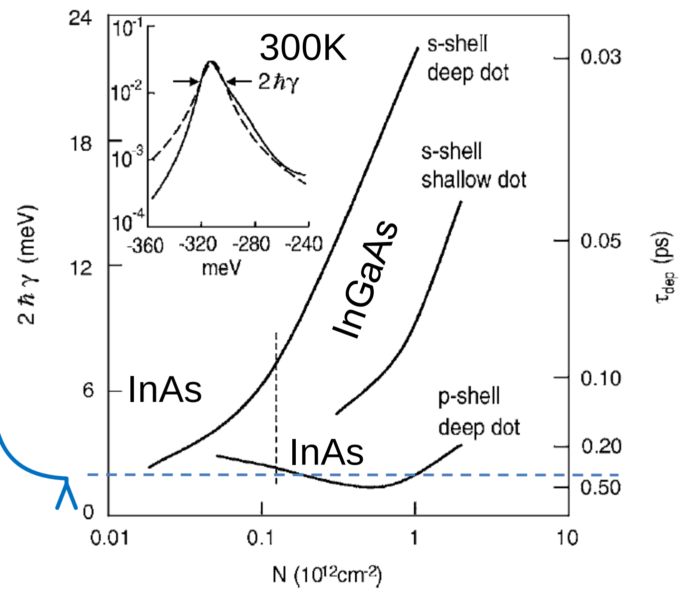
Rabi frequency

$$\Omega_R = 4.7 \times 10^{12}\, s^{-1} = \frac{\wp E}{\hbar}$$

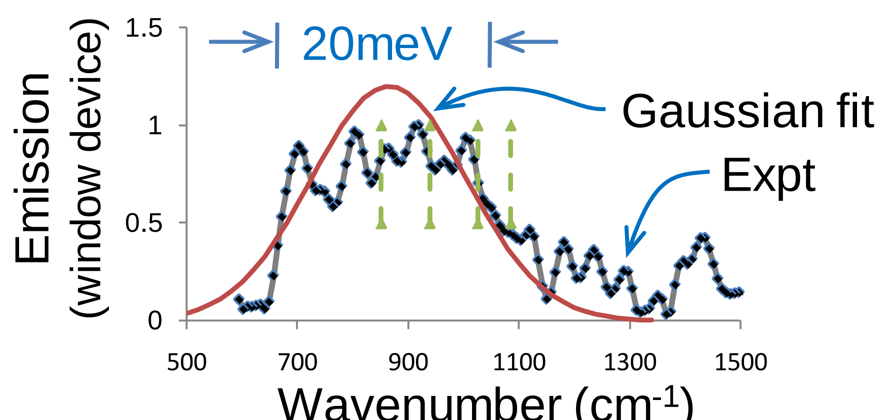
Dephasing

$$\gamma = 1.26 \times 10^{12}\, s^{-1}$$

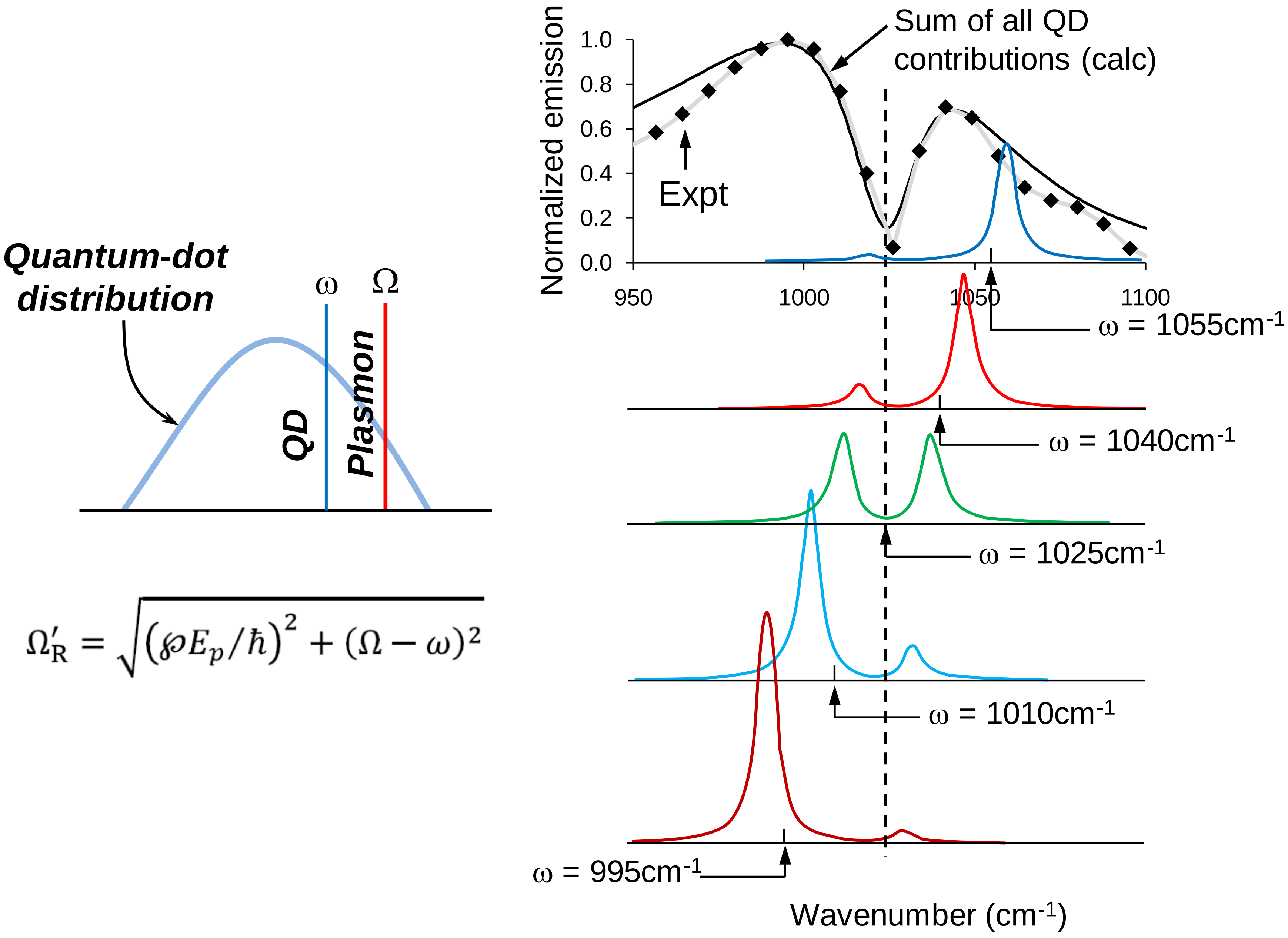
Lorke, WWC, Nielsen, Seebeck, Gartner and Jahnke, PRB **74**, 035334, 2006 (with polaron, memory, off-diagonal correlations)



Inhomogeneous broadening



Quantum dot contributions to electroluminescence



$$\Omega_R' = \sqrt{\left(\wp E_p/\hbar\right)^2 + (\Omega - \omega)^2}$$

Collaborators

Theory

University of Bremen: Michael Lorke and Frank Jahnke

Technical University, Berlin: Alexander Carmele and Andreas Knorr

Experiment

Sandia: Brandon Passmore and Eric Shaner

U. Mass: Dan Wasserman

Princeton: Stephen Lyon