Optics and Quantum Optics with Semiconductor Nanostructures

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Overview

- background: optics with atoms
- semiclassical semiconductor optics
- semiconductor quantum optics:
  "which way" experiments and light – matter entanglement

Collaborators

theory: Kira, Hoyer et al., Marburg
Hader, Moloney et al., Tucson

experiments: Gibbs/Khitrova et al., Tucson,
Stolz et al., Rostock


Marburg

Marburg

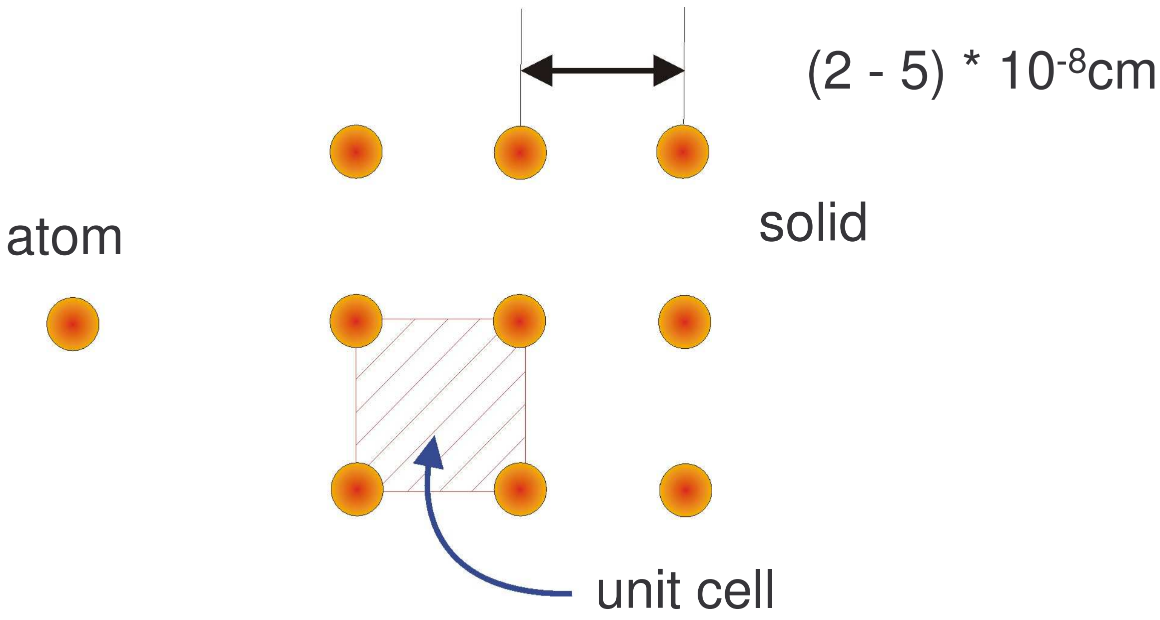
You do not really understand something unless you can explain it to your grandmother (*Albert Einstein*)

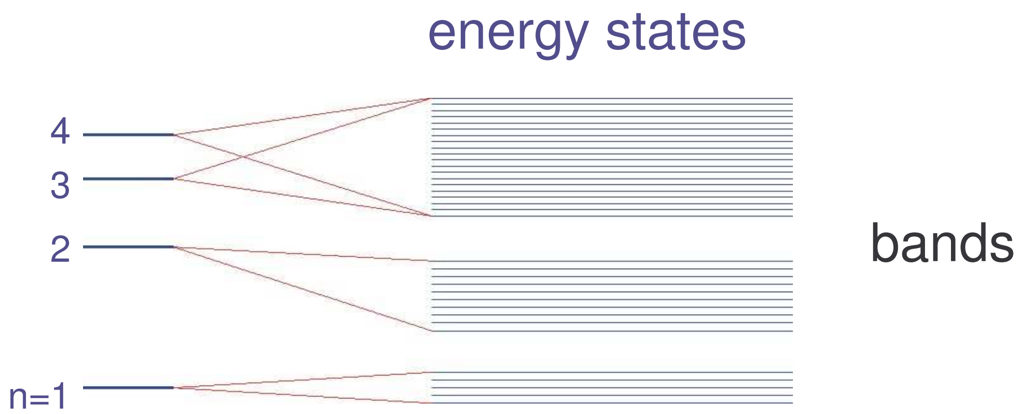
From Atoms to Solids …

atom

optical absorption/emission =
transitions between atomic levels

From Atoms to Solids …

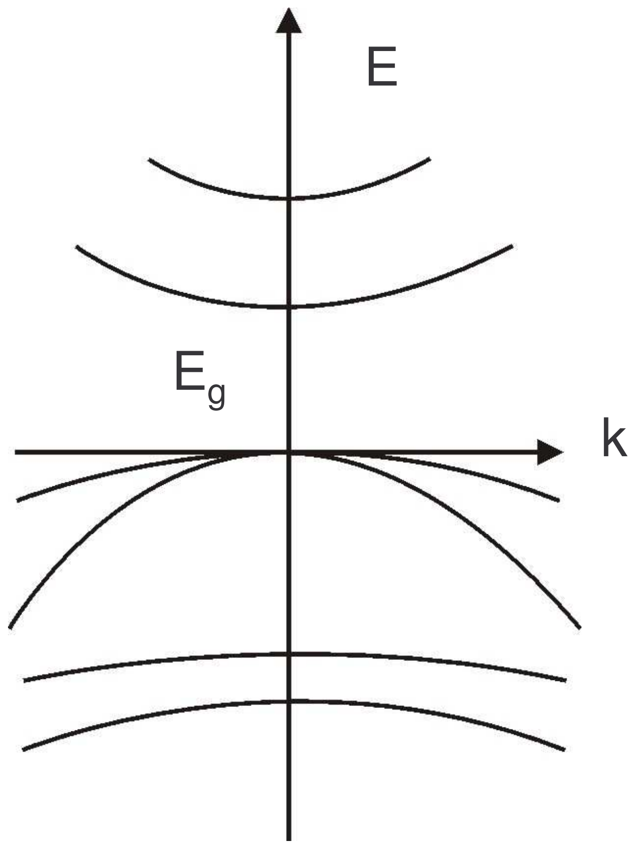




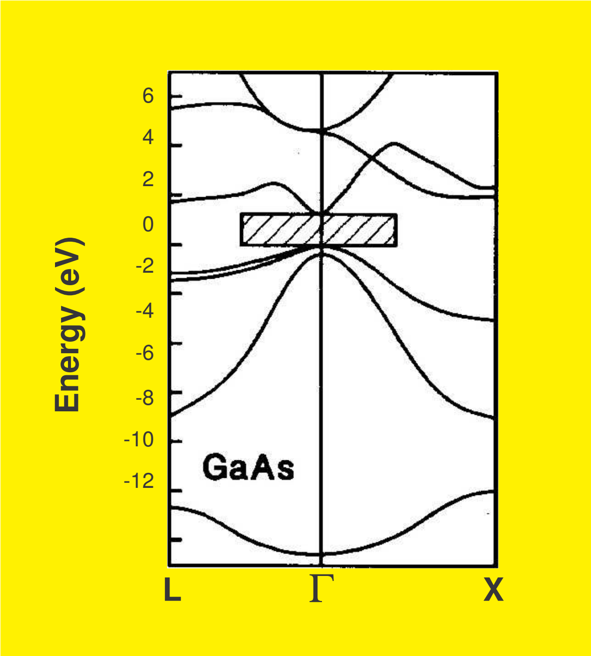
Bandstructure

possible energy
values of electrons
in crystal

intrinsic semiconductor:
full valence band(s),
empty conduction band



Realistic Bandstructure GaAs



effective mass approximation

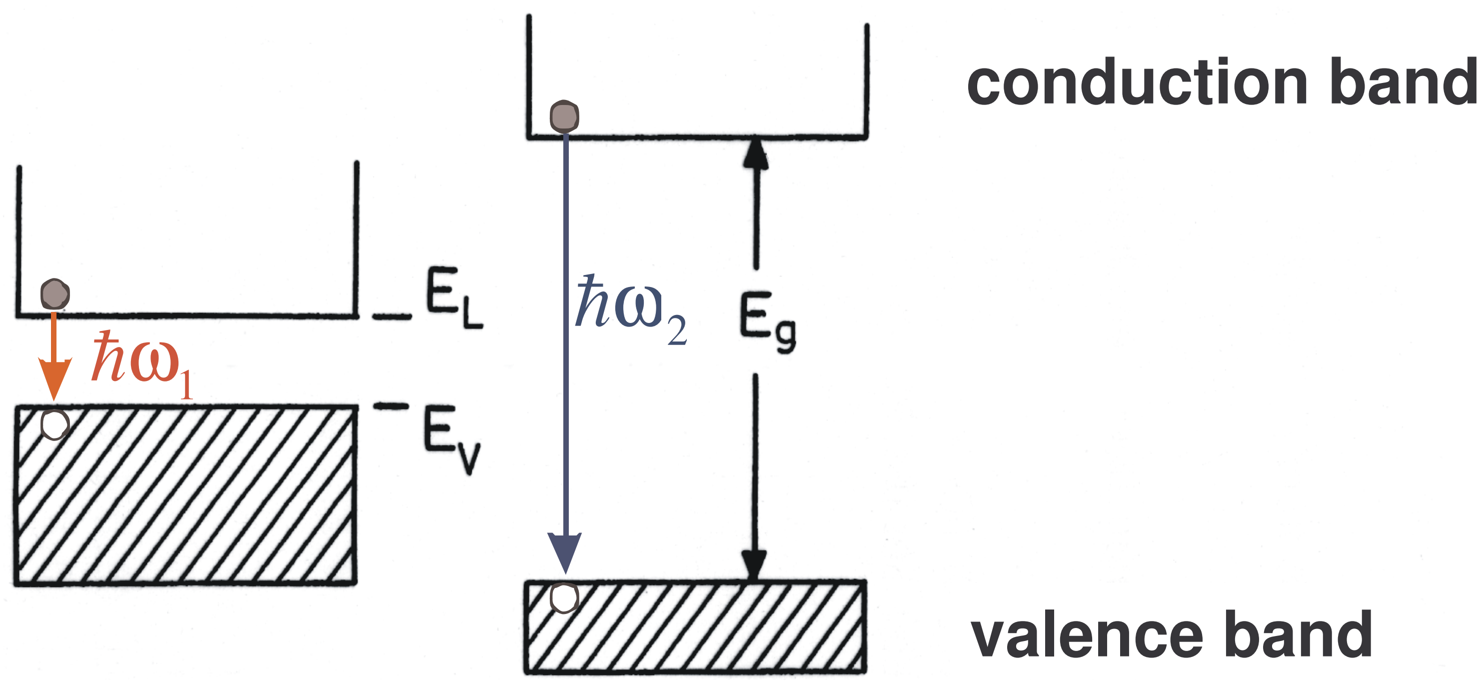
$$\varepsilon_{c\mathbf{k}} = \frac{\hbar^2 k^2}{2m_c} + \varepsilon_{g0}$$

$$\varepsilon_{v\mathbf{k}} = \frac{\hbar^2 k^2}{2m_v}$$

often: photon momentum $\hbar K \ll$ typical carrier momentum

$\Rightarrow$ perpendicular transitions, $K \simeq 0$

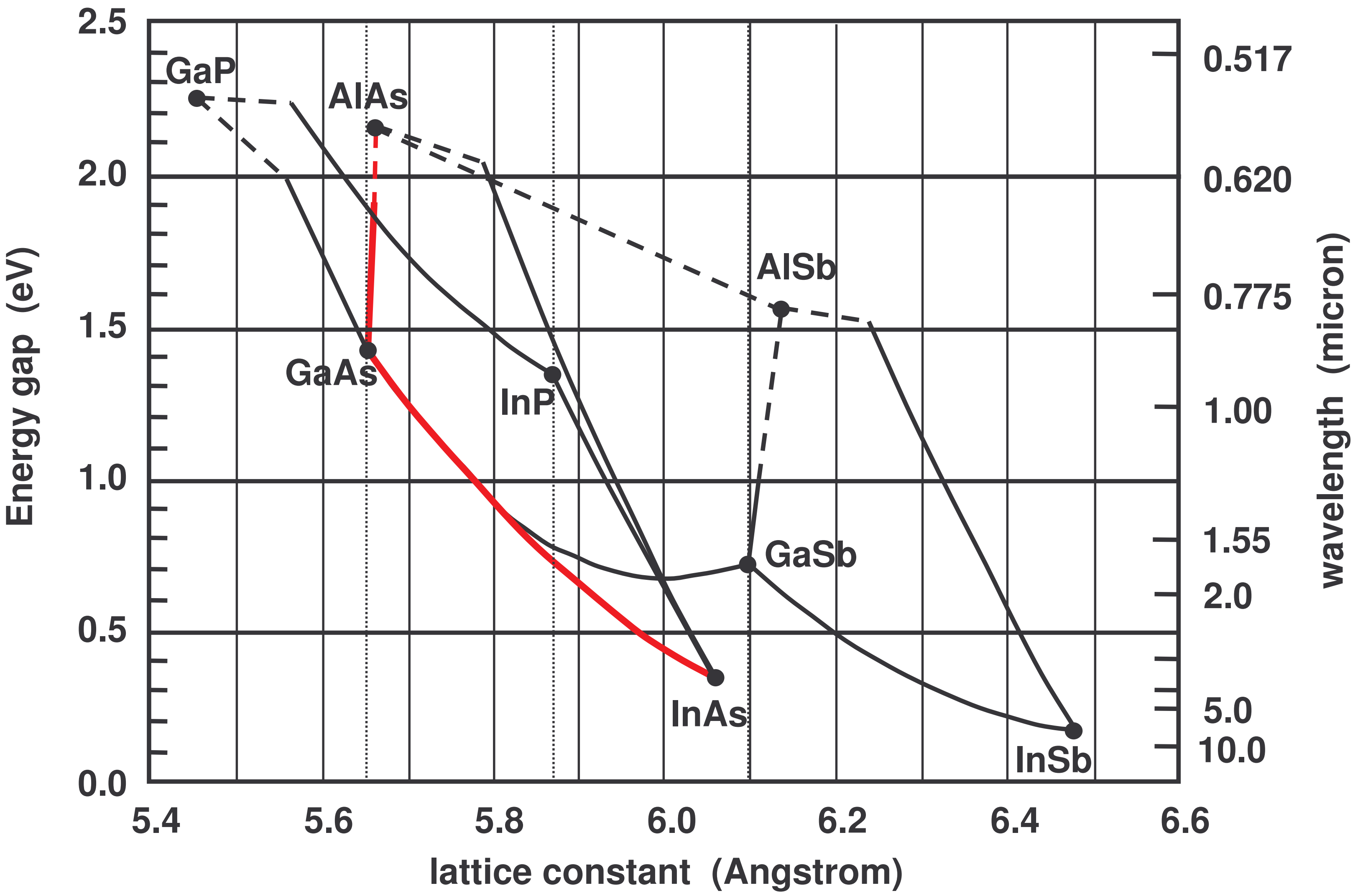
Energy Gap in Semiconductors



gap energy determines frequency and therefore color (wavelength) of absorbed and/or emitted light

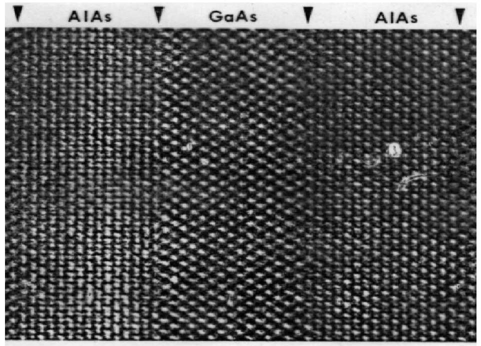

LEDs based on group-III nitride materials
(Fraunhofer-Institut Freiburg)

Bandgaps of III-V Alloys (300 K)

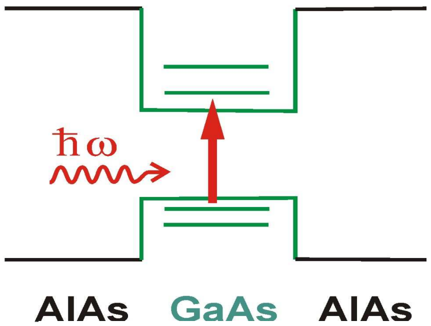


Quasi-Two Dimensional Structure

TEM picture: quantum well structure



band gap at Γ-point (direct semiconductor)

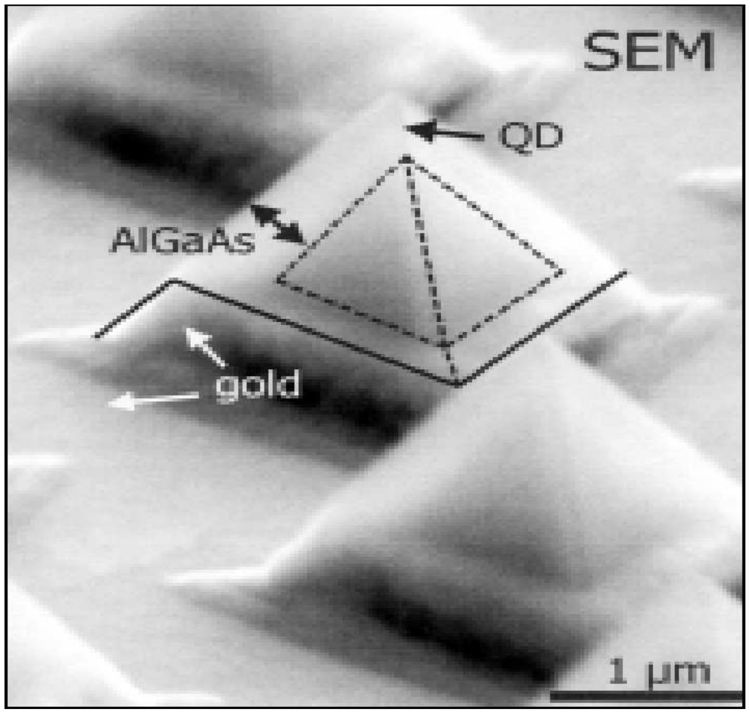


discrete states (z direction) and continuous bands (x-y plane)

Semiconductors as Designer Materials

- quantum well = two-dimensional electronic mobility
- quantum wire = one-dimensional electronic mobility
- quantum dot = no (zero-dimensional) electronic mobility

self organized
quantum dots



Interband Light-Matter Interaction: Semiclassical Theory

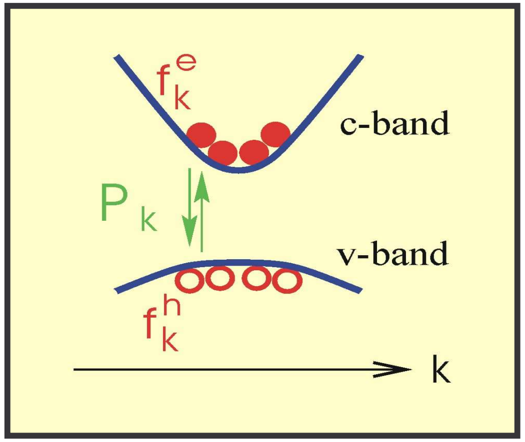
classical Maxwell's wave equation

macroscopic optical polarization

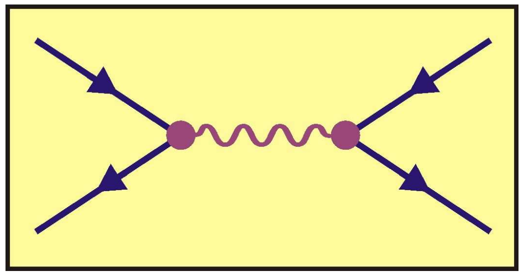
$$\left[\frac{\partial^2}{\partial z^2} - \frac{n^2(z)}{c^2}\frac{\partial^2}{\partial t^2}\right] E = \mu_0 \frac{\partial^2}{\partial t^2} P$$

semiconductor:
Bloch basis

$$P = \sum_k d^*_{cv} P_k + c.c.$$



Coulomb interaction of charge carriers $\rightarrow$ quantum mechanical many-body problem of interacting Fermions

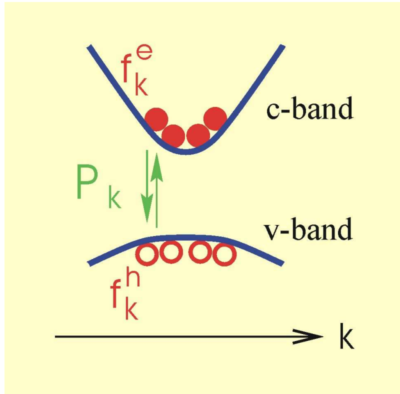


V_{Coul}

Semiconductor Bloch Equations (SBE)

$$\left[i\hbar\frac{\partial}{\partial t} - \epsilon_k^e - \epsilon_k^h\right] P_k = \left[1 - f_k^e - f_k^h\right] \Omega_k + \frac{\partial}{\partial t} P_k|_{corr}$$

$$i\hbar\frac{\partial}{\partial t}\, f_k^a = -\Omega_k(t) P_k^* + \Omega_k^* P_k + \frac{\partial}{\partial t} f_k^a|_{corr}$$



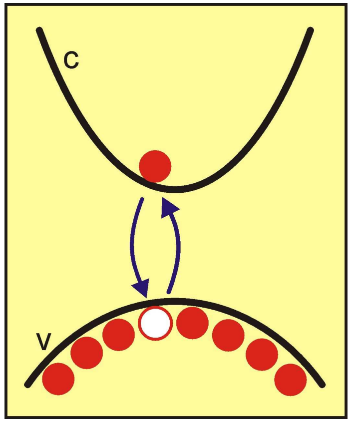
field renormalization $$\Omega_k(t) = d_{cv}\; E^{QW}(t) + \sum_{k'} V_{k-k'}\; P_{k'}(t)$$

energy renormalization $$\epsilon_k^a(t) \;=\; \varepsilon_k^a - \sum_{k'} V_{k-k'}\; f_{k'}^a(t)$$

- nonlinearities: phase space fillinging, gap renormalization,
  Coulomb attraction
- correlation effects: scattering, dephasing, screening, …

Wannier Excitons

- 2 parabolic bands



electron-hole pair
interband Coulomb
attraction

- wavefunction $\Psi_{\mathrm{eh}}(r_{\mathrm{e}}, r_{\mathrm{h}}) = \Phi_K(R)\phi_\lambda(r)$

- relative motion
  (Wannier equation)

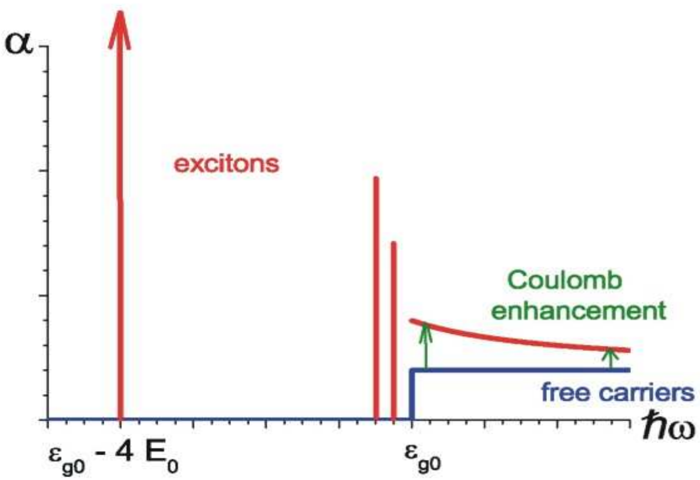
$$\left(\frac{\hbar^2\nabla^2}{2\mu} - V(r)\right)\phi_\lambda(r) = E_\lambda\phi_\lambda(r)$$

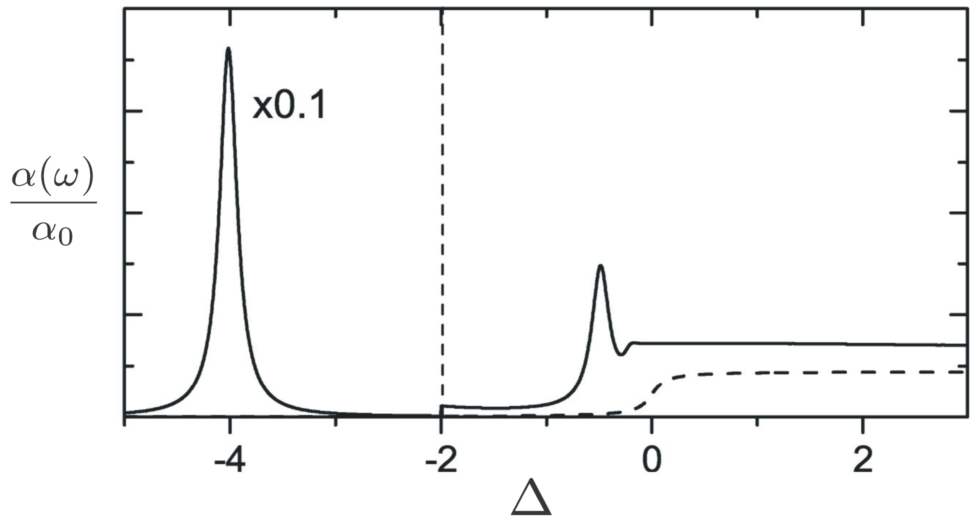
Coulomb potential

- hydrogen atom like solutions,
  Wannier excitons = quasi atoms (finite lifetime < nanoseconds)

Wannier Excitons

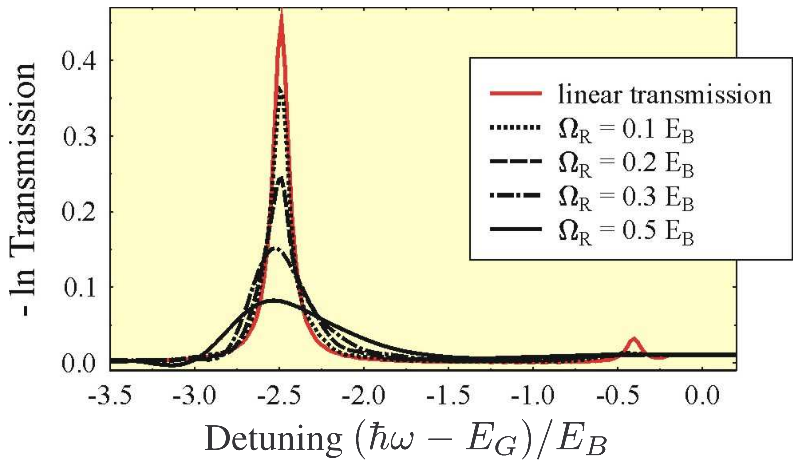
• linear absorption → Elliott formula





• linear optics: excitonic resonances
• INTERACTION induced resonances, not just transitions between bands

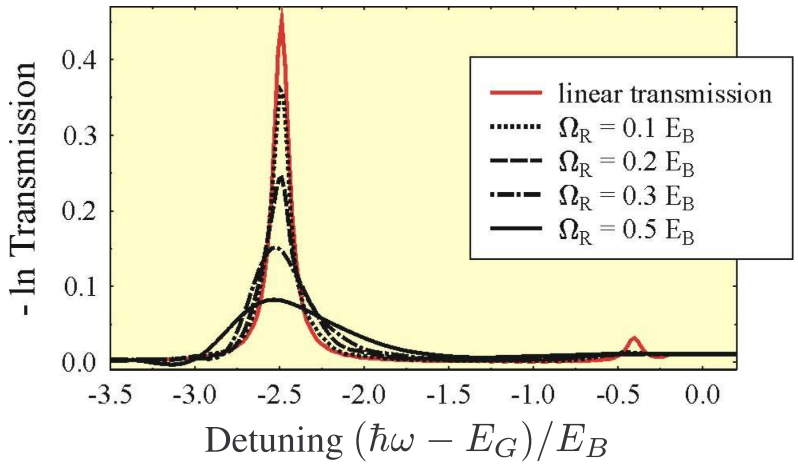
Exciton Saturation



F. Jahnke, M. Kira, and S.W. Koch,
Z. Physik B 104, 559 (1997)
Born-Markov approximation

saturation via excitation induced dephasing (EID)
= Coulomb induced destructive interference
between different P_k

Exciton Saturation



F. Jahnke, M. Kira, and S.W. Koch,
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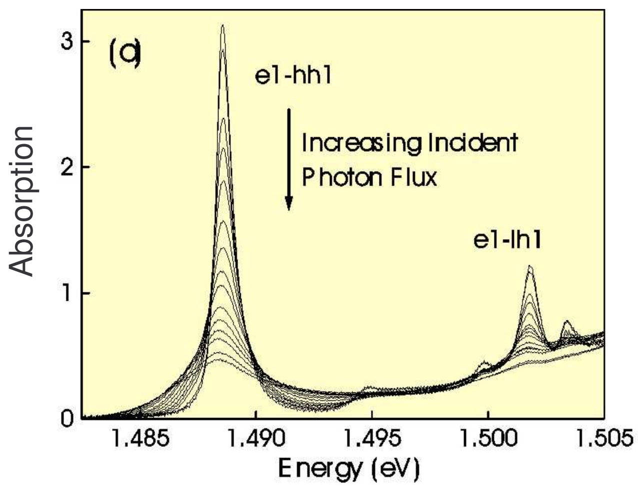
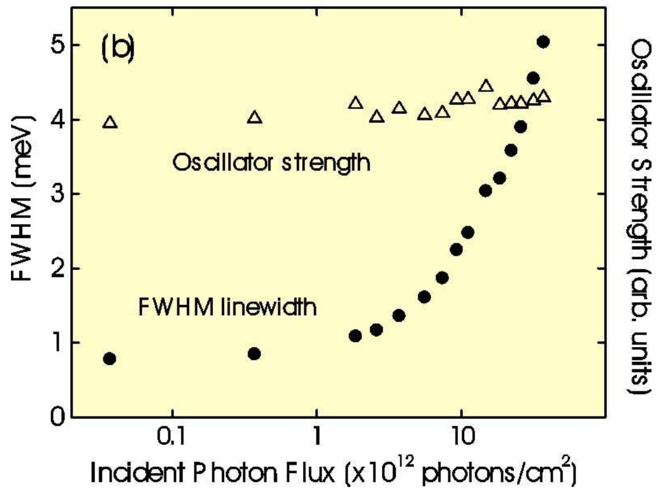
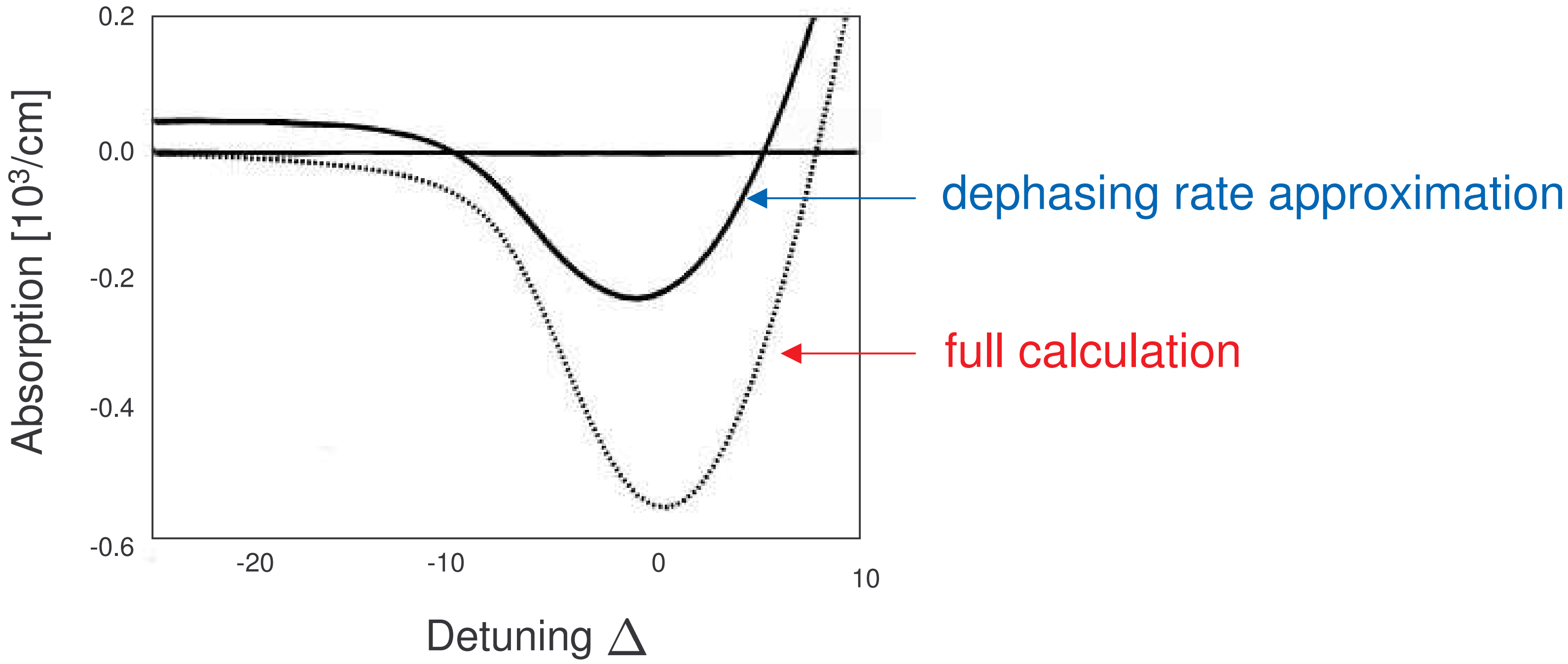




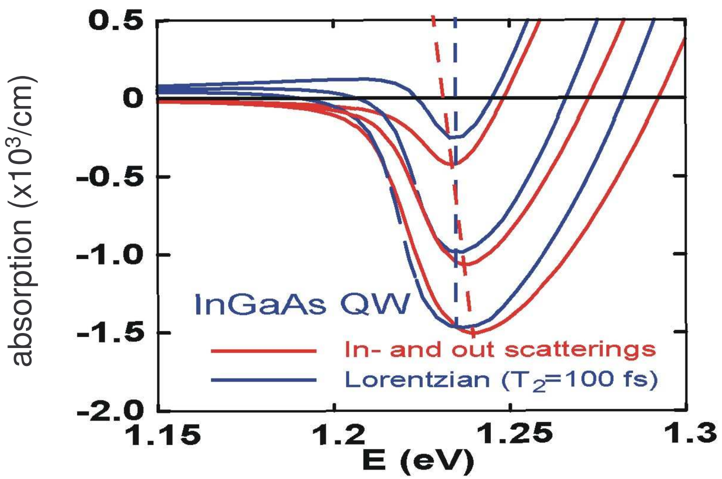
- experiment: InGaAs/GaAs QW
- Khitrova, Gibbs, Jahnke, Kira, Koch, Rev. Mod. Phys. 71, 1591 (1999)
- EID first observed in 4-wave mixing, Wang *et al.* PRL 71, 1261 (1993)

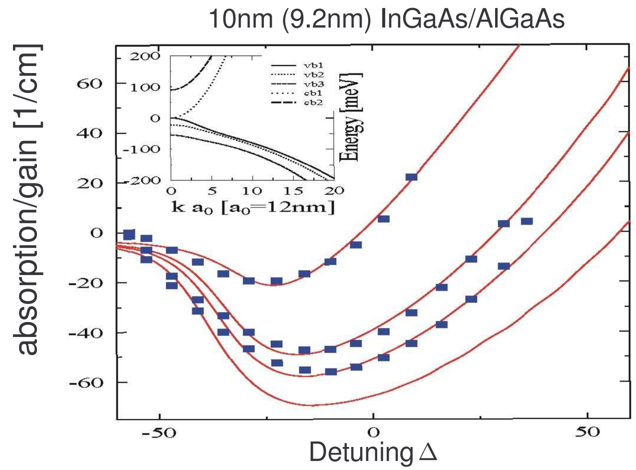
Lineshape Problem



- $\Delta = (\hbar\omega - E_G)/E_B$
- gain of two-band bulk material
- nondiagonal scattering contributions $\rightarrow$ lineshape modification, no absorption below the gap

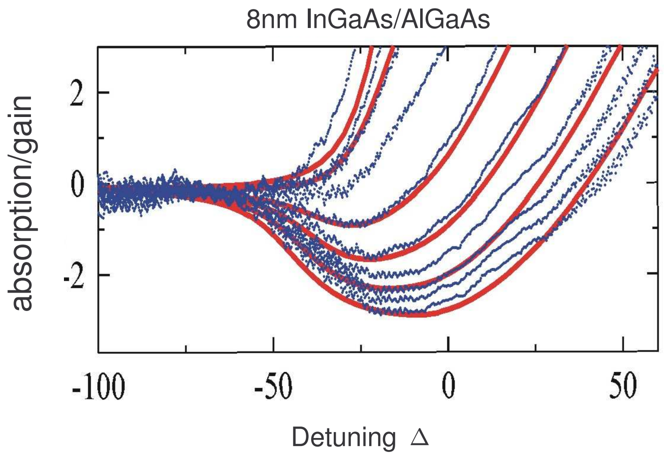
Optical Gain in Semiconductors: Theory and Experiment





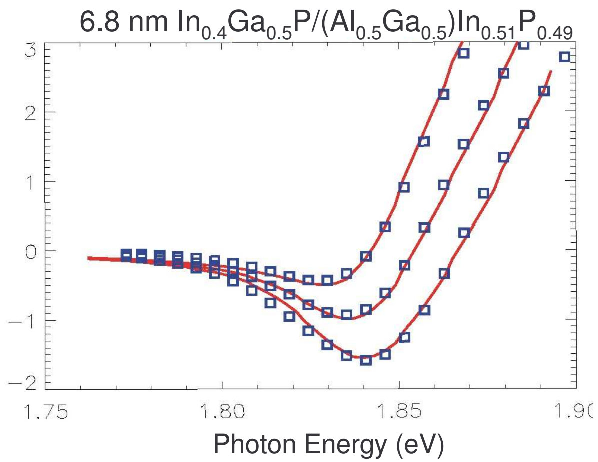
N=1.6, 2.2, 2.5, 3.0*10^{12}/cm^2

exp: D. Bossert et al., theory: A. Girndt et al., Marburg



Current 0-20mA… Density 0.6-3.0x10^{12}cm^{-2}

exp: C. Ellmers et al., theory: A. Girndt et al. Marburg



Courtesy of W.W. Chow, P.M. Smowton, P. Blood, A. Grindt, F. Jahnke, and S.W. Koch

Summary of Semiclassical Phenomena

- quantitative understanding of interaction phenomena
- strong experiment – theory interactions
- predictive capability of theory

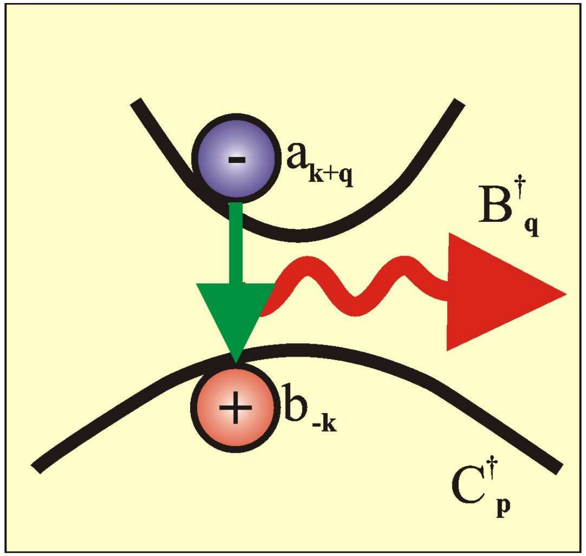
CHALLENGES:

- modified photonic environment (nano optics with nano structures)
- optimized design for specific applications
- nonequilibrium phenomena ….

Selected References:

- Haug/Koch, "Quantum Theory of the Optical and Electronic Properties of Semiconductors" 4th ed., World Scientific Publ. (2004)
- Khitrova et al., Rev. Mod. Phys. **71**, 1591 (1999)

Quantized Light-Matter Interaction

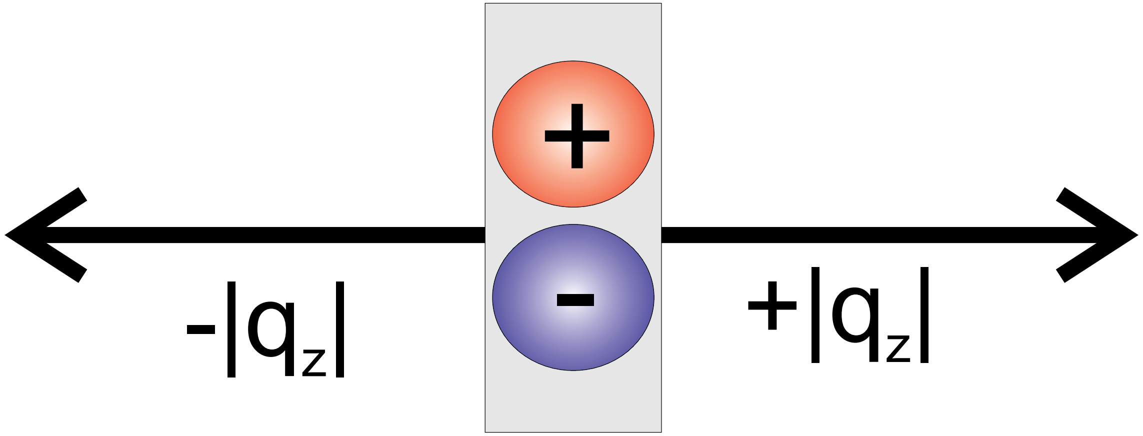


$$H_{cf}^{qm} = \sum A(k,q) a_{k+q} b_{-k} B_q^{\dagger} + \mathrm{h.c.}$$

where $A(k,q)$ is proportional to dipole matrix element and mode strength at the QW position

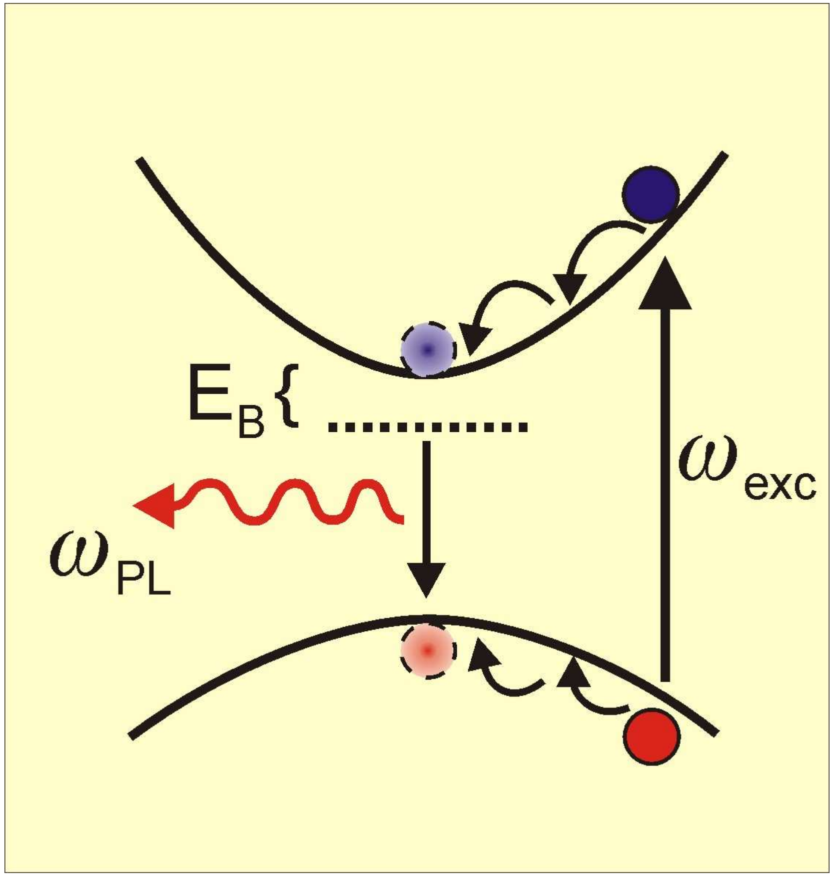
Kira et al., Prog. Quantum. Electron. **23**, 189 (1999)

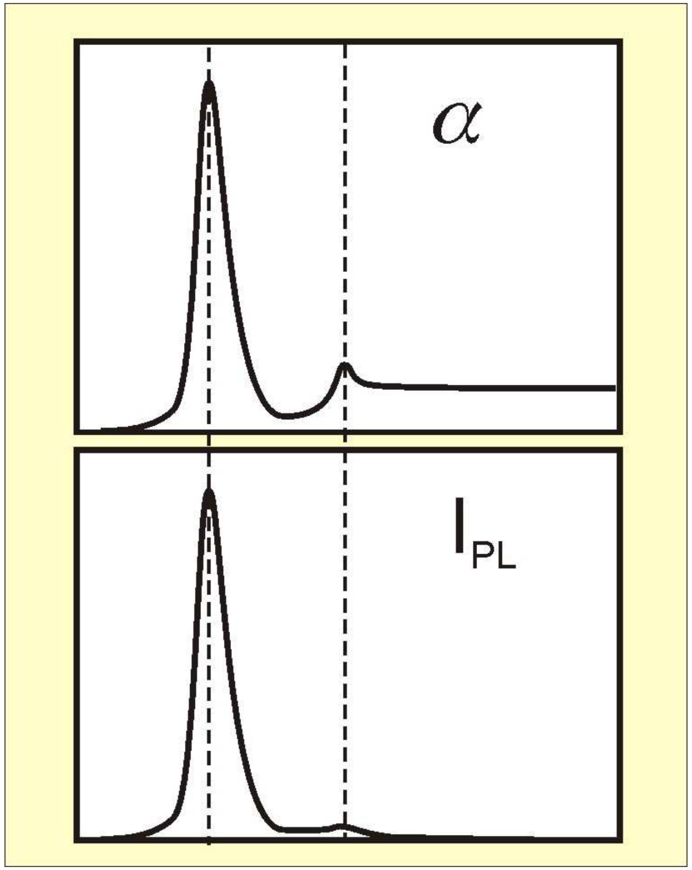
Spontaneous Emission from Quantum Wells



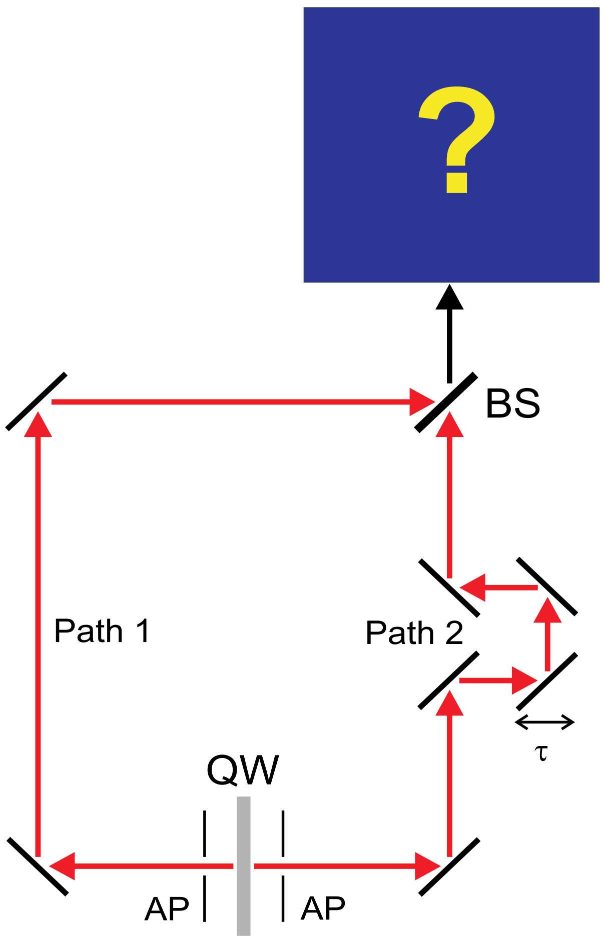
- recombination in electron-hole system
- no translational invariance perpendicular to QW
- no q_z momentum conservation
- emission occurs simultaneously to left and right, i.e. with $+|q_z|$ and $-|q_z|$

Non Resonantly Excited Photoluminescence





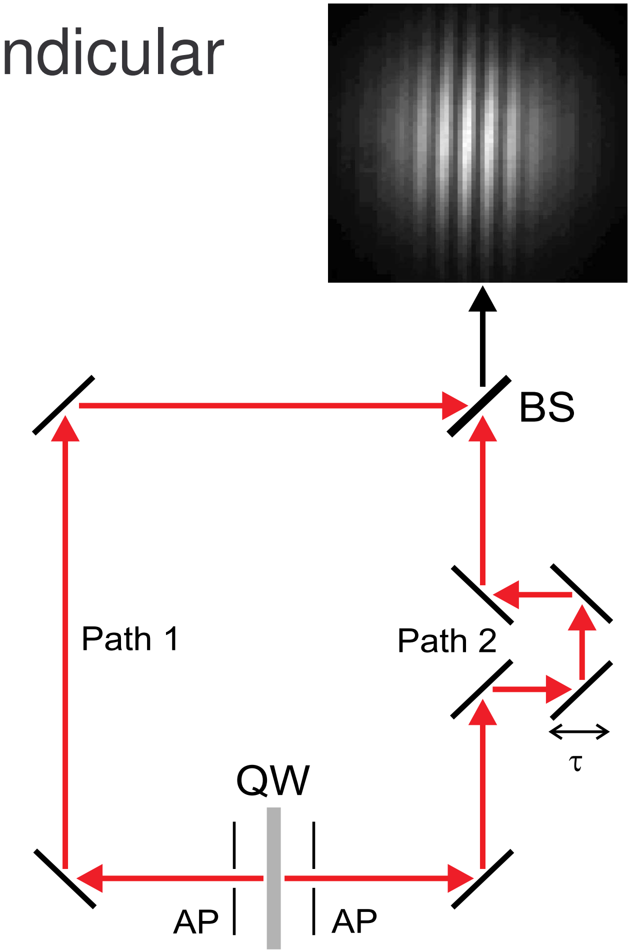
Experiments



- non resonant excitation of QW (weak excitation)
- incoherent (random) emission at exciton resonance
- different emission directions collected in interferometer setup
- measurement combines emission to the left and right directions (less than one photon in interferometer)
- control of phase ϕ via delay τ

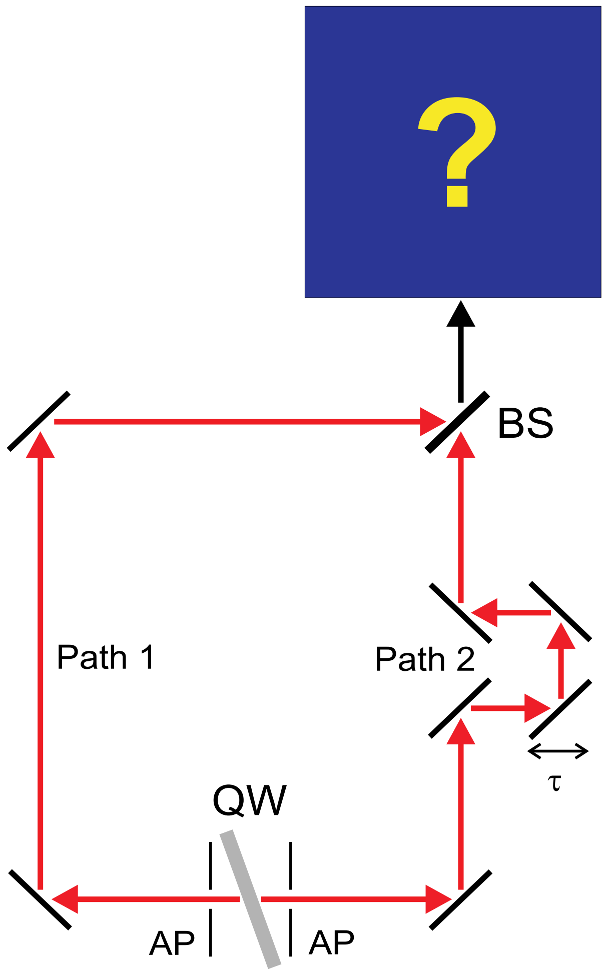
Experiments (I)

- QW perpendicular



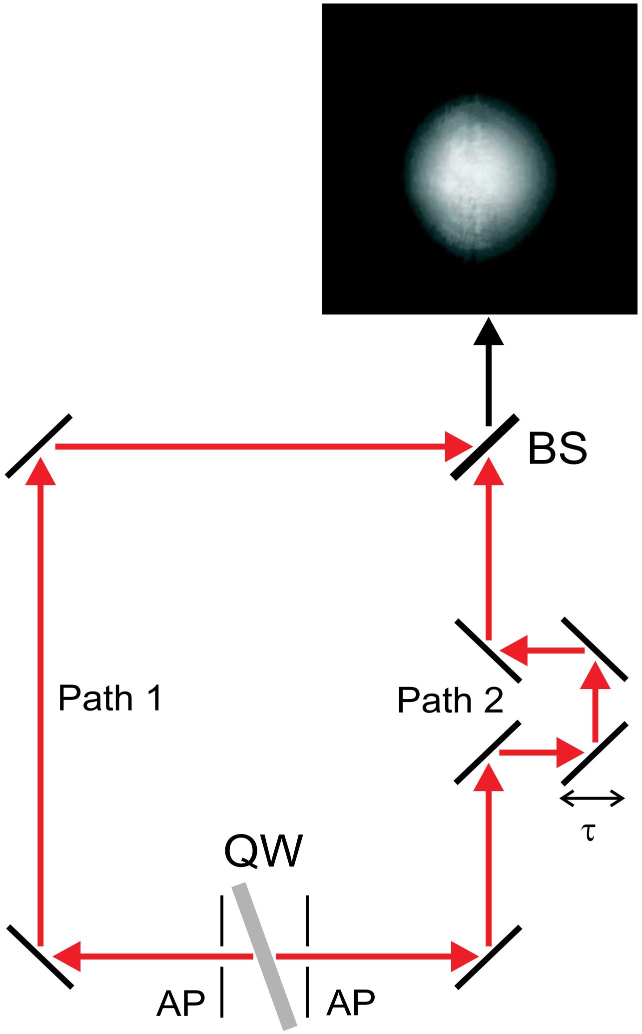
Experiments (II)

- QW tilted

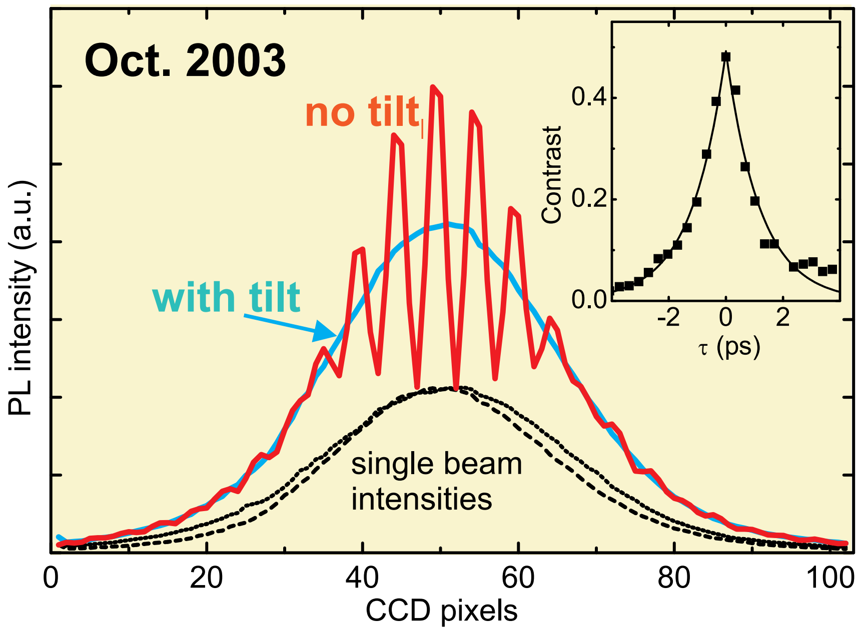


Experiments (II)

- QW tilted



Experiments (III)



- clear interferences visible if QW **NOT** tilted
- interferences vanish if QW tilted
- Hoyer et al. PRL **93**, 067401 (2004)

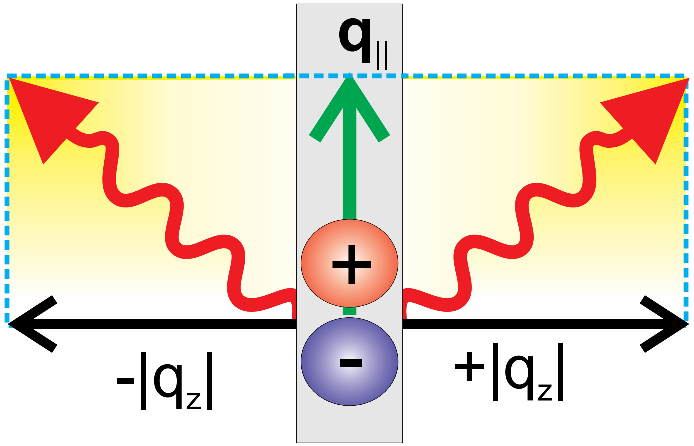
Summary of Experimental Observations

- interferences seen in incoherent (single photon) emission
- $< E >= 0$, but intensity $< E_L E_R >$ shows interferences
- interference shows strong directional sensitivity

Summary of Experimental Observations

- interferences seen in incoherent (single photon) emission
- $< E >= 0$, but intensity $< E_L E_R >$ shows interferences
- interference shows strong directional sensitivity
- effects predicted in Prog. Quantum. El. **23**, 189 (1999)
- origin of effects: light-matter entanglement & which-way interferences

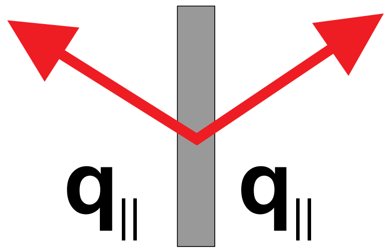
Spontaneous Emission from Quantum Wells



- electron-hole recombination
- simultaneous emission in $+|q_z|$ and $-|q_z|$ directions
- photon emission with same $q_{||}$
- recoil momentum transferred to carrier system

Explanation of Interferences (I)

- CASE A: Emission with same $q_{||}$



photon

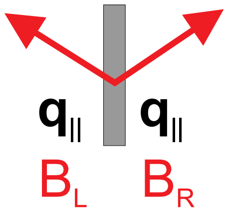
- emission to the left $|-q_z, \mathbf{q}_{||}\rangle \otimes |\Psi(\mathbf{q}_{||})\rangle$

many-body wavefunction with recoil

- emission to the right $|+q_z, \mathbf{q}_{||}\rangle \otimes |\Psi(\mathbf{q}_{||})\rangle$

➡ paths not distinguishable with respect to carrier system (i.e. no entanglement)

Explanation of Interferences (II)



$$[|-q_z,\mathbf{q}_{||}\rangle + e^{i\Phi}|+q_z,\mathbf{q}_{||}\rangle] \otimes |\Psi(\mathbf{q}_{||})\rangle + \text{rest}$$

variable phase

$$\begin{aligned}\langle\Psi|B_L^\dagger B_R|\Psi\rangle &= e^{i\Phi}\langle -q_z,\mathbf{q}_{||}|B_L^\dagger B_R|+q_z,\mathbf{q}_{||}\rangle\langle\Psi(\mathbf{q}_{||})|\Psi(\mathbf{q}_{||})\rangle \\ &= e^{i\Phi} I_{L,R}\end{aligned}$$

$= 1$

interferometry:

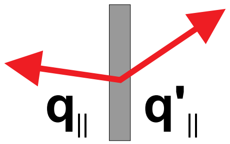
$$I = \langle D^\dagger D\rangle = \langle B_L^\dagger B_L\rangle + \langle B_R^\dagger B_R\rangle + 2Re[\langle B_L^\dagger B_R\rangle] = 2I_{L,R}(1+\cos\Phi)$$

emission intensity — I_L to the left — I_R to the right — interference

INTERFERENCE can be seen

Explanation of Entanglement (I)

- CASE B: Emission with different $q_{||}$



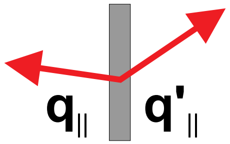
photons

$$|-q_z, \mathbf{q}_{||}\rangle \otimes |\Psi(\mathbf{q}_{||})\rangle + e^{i\Phi}|+q'_z, \mathbf{q}'_{||}\rangle \otimes |\Psi(\mathbf{q}'_{||})\rangle + \mathrm{rest}$$

many-body wavefunction with recoil

- emission to the left $|-q_z, \mathbf{q}_{||}\rangle \otimes |\Psi(\mathbf{q}_{||})\rangle$
- emission to the right $|q'_z, \mathbf{q}'_{||}\rangle \otimes |\Psi(\mathbf{q}'_{||})\rangle$
- $\langle\Psi(\mathbf{q}_{||})|\Psi(\mathbf{q}'_{||})\rangle = 0$ ➡ paths identified by entanglement

Explanation of Entanglement (II)



$$|-q_z, \mathbf{q}_{||}\rangle \otimes |\Psi(\mathbf{q}_{||})\rangle + e^{i\Phi}|+q'_z, \mathbf{q}'_{||}\rangle \otimes |\Psi(\mathbf{q}'_{||})\rangle + \text{rest}$$

- emission to the left (B_L) und to the right (B_R) is combined in detector D = B_L +B_R

$$I = \langle D^\dagger D\rangle = \langle B_L^\dagger B_L\rangle + \langle B_R^\dagger B_R\rangle + 2Re[\langle B_L^\dagger B_R\rangle]$$

emissions intensity — I_L to the left — I_R to the right — interference

$$\langle\Psi|B_L^\dagger B_R|\Psi\rangle = e^{i\Phi}\langle -q_z, \mathbf{q}_{||}|B_L^\dagger B_R|+q'_z, \mathbf{q}_{||}\rangle\langle\Psi(\mathbf{q}_{||})|\Psi(\mathbf{q}'_{||})\rangle$$

$= 0$

➡ NO interference pattern due to entanglement

Theory of Entanglement-Interferences

semiconductor luminescence equations PRL 97, 5170 (1997)

- photon-assisted correlations $\Delta \sum_{\mathbf{k}} \langle B^{\dagger}_{q_z,\mathbf{q}_{||}} b_{-\mathbf{k}} a_{\mathbf{k}+\mathbf{q}_{||}} \rangle$
- photon correlations $\Delta \langle B^{\dagger}_{q_z,\mathbf{q}_{||}} B_{q'_z,\mathbf{q}'_{||}} \rangle$
- in the presence of Coulomb interaction

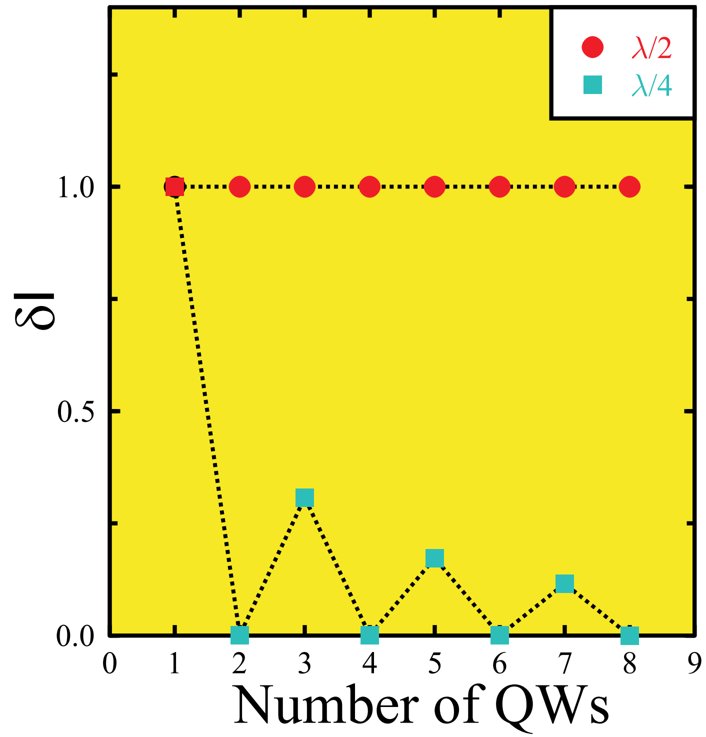
- QUESTION: WHAT HAPPENS IF WE TAKE MANY QUANTUM WELLS ?

Theory of Entanglement-Interferences

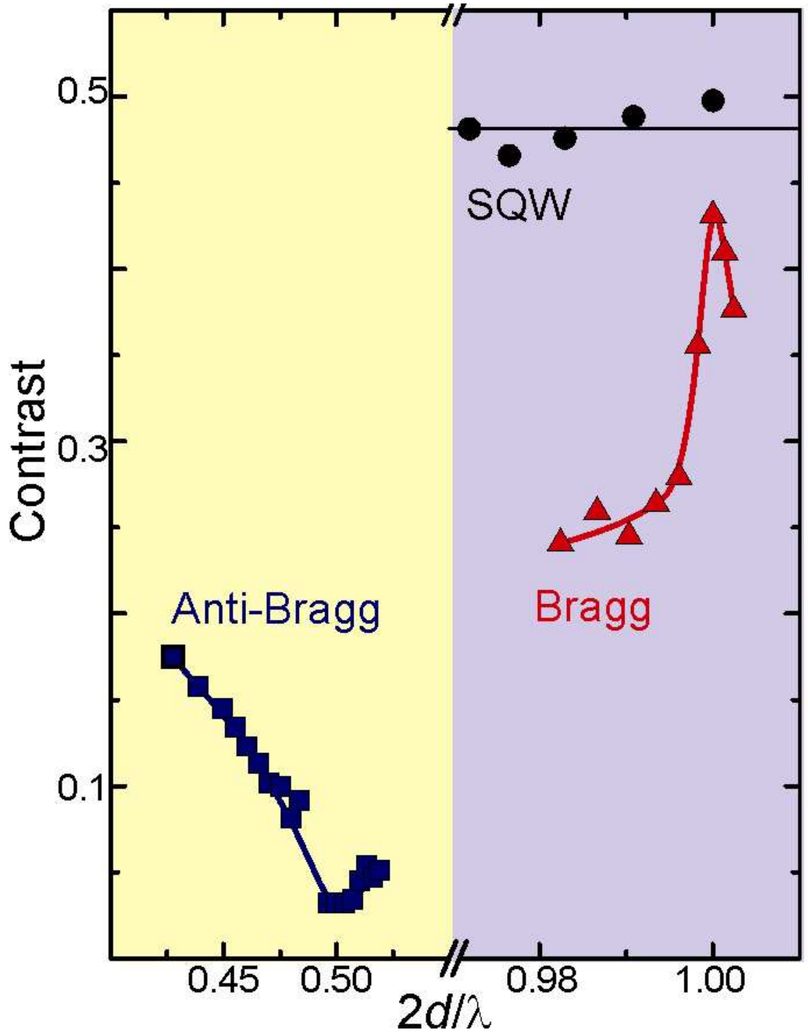
Predictions for n quantum wells with spacing d

- perfect interferences for Bragg $d = \lambda/2$
- no interferences for anti-Bragg $d = \lambda/4$ (n-even)

Prog. Quantum. El. **23**, 189 (1999)



Entanglement-Interference Experiment (IV)



- interferences seen in multiple QW system with $\lambda/2$ spacing
- interferences vanish in multiple QW system with $\lambda/4$ spacing
- $\lambda/4$ spacing leads to complete randomizing of emission to the left and to the right
- confirmation of theoretical predictions

Summary of Entanglement-Interferences

- incoherent emission to the left and to the right are entangled with the many-body carrier system
- emission to the left and to the right with same $q_{||}$ is not entangled
- emission to the left and to the right with same $q_{||}$ is entangled
- description of entanglement via photon-carrier and photon-photon correlations of the type: $\Delta\langle B^{\dagger}_{q_z,\mathbf{q}_{||}} \sum_{\mathbf{k}} b_{-\mathbf{k}} a_{\mathbf{k}+\mathbf{q}_{||}}\rangle$ and $\Delta\langle B^{\dagger}_{q_z,\mathbf{q}_{||}} B_{q'_z,\mathbf{q}_{||}}\rangle$
- more in: Hoyer et al. PRL **93**, 067401 (2004)

Summary

- variety of novel quantum optical effects in semiconductors
- strong experiment – theory interactions

MANY CHALLENGES:

- optimization and application of non-classical properties (quantum information science, …)
- modified photonic environment (phot. x-tals, …)
- role of incoherent excitons, biexcitons, ….

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- Haug/Koch, "Quantum Theory of the Optical and Electronic Properties of Semiconductors" 4th ed., World Scientific Publ. (2004)
- Khitrova et al., Rev. Mod. Phys. **71**, 1591 (1999)
- Kira et al., Prog. Quantum. Electron. **23**, 189 (1999)