Magneto-Optical Properties of Quantum Nanostructures

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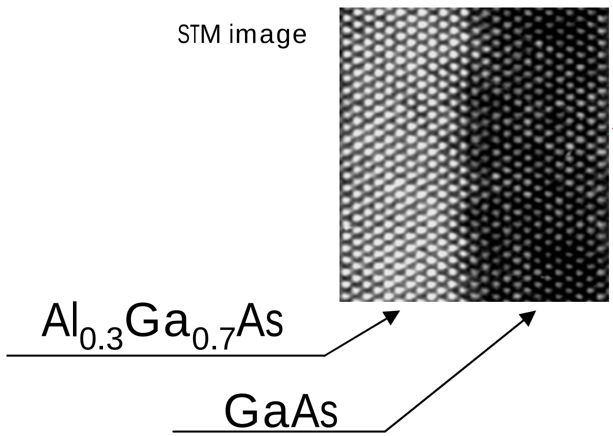
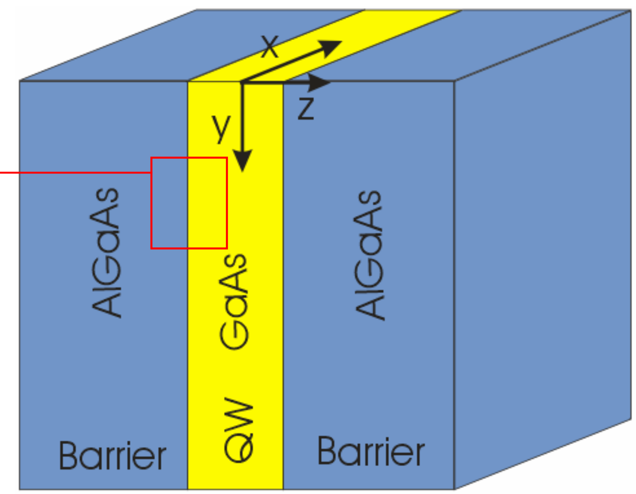
Outline:

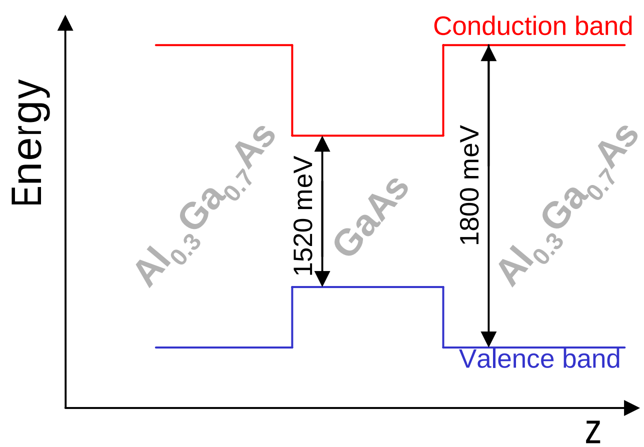
- Semiconductor quantum nanostructures
- Magneto-optical laboratory in Prague
- 2D electron gas in the in-plane magnetic field
- Superlattice in in-plane magnetic fields

Semiconductor quantum wells

Quantum well (QW) = semiconductor device with
1D quantum confinement of particles







Preparation:

Mostly MBE

Other materials:

$In_xGa_{1-x}As/GaAs$

$Cd_xZn_{1-x}Te/CdTe$

$Cd_xMn_{1-x}Te/CdTe$…

Physics of quantum wells

Basic quantum mechanics…..

Hamiltonian:

$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{p_z^2}{2m} + V(z)$$

$\Longrightarrow$

Energy spectrum:

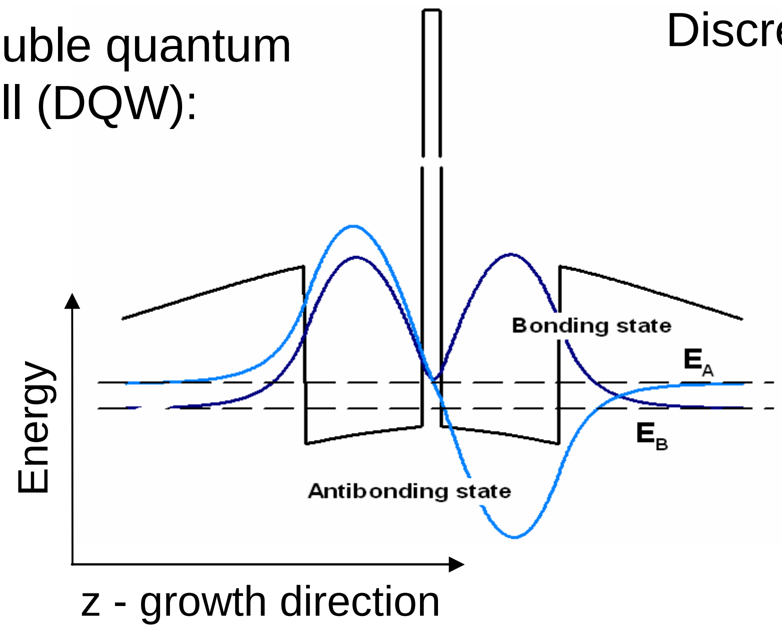
$$E_i(k_x, k_y) = \underbrace{E_i}_{\text{Discrete subband energy}} + \underbrace{\frac{\hbar^2 k_x^2 + \hbar^2 k_y^2}{2m}}_{\text{Free motion in QW plane}}$$

Discrete subband energy

Free motion in QW plane

$\Downarrow$

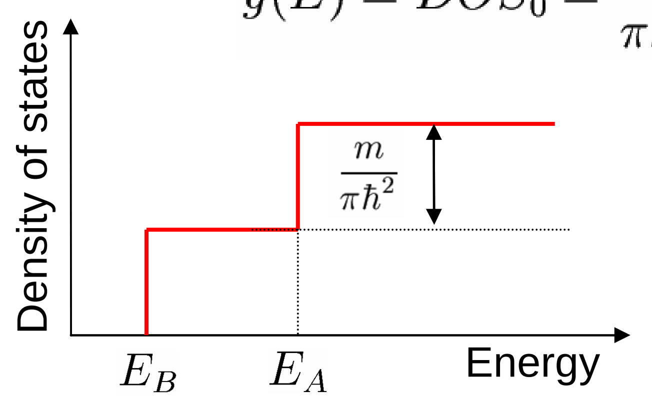
Double quantum well (DQW):



DQW = the simplest 3D system

Constant density of states (DOS):

$$g(E) = DOS_0 = \frac{m}{\pi\hbar^2}$$



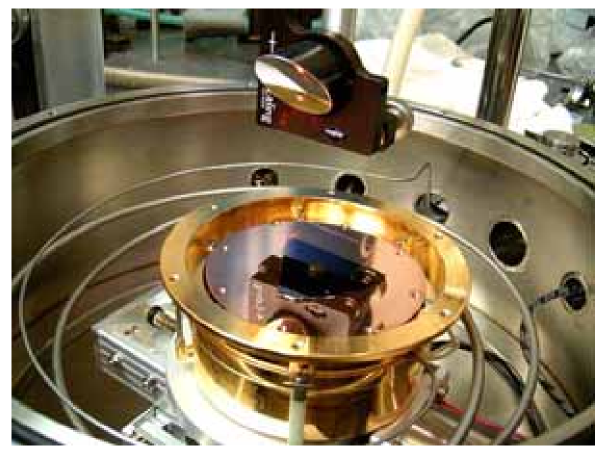
Magneto-optical laboratory MFF UK

Fourier transform spectrometer Bruker IFS 66/S for the near-infrared optical spectroscopy
(detection range 0.5-2 eV)

Spatially resolved PL - cryostat Cryovac equipped with x-y movement
(temperature 10-300 K, resolution 50µm)

Superconducting solenoid in optical cryostat allowing measurements in both Voigt and Faraday configurations
(magnetic field 11.5 T, temperature 1.4-300 K)

Experimental techniques: Polarization sensitive luminescence, reflectance, photoconductivity, transmittance…



Tunable Ti-sapphire laser and photoluminescence excitation spectroscopy (coming soon…..)

Cooperation with GHMFL

Grenoble High Magnetic Field Laboratory

Resistive solenoids up to 23 T (32 T)

Optical laboratory:

wide range of optical experiments, esp. low-temperature photoluminescence

Quantum wells in in-plane magnetic fields

…ansatz for the wave function:

$$\psi_{n,k_x,k_y}(x,y,z) = e^{i(k_x x + k_y y)} \chi_{n,k_x}(z)$$

Hamiltonian of the quantum well system subject to the in-plane magnetic fields:

$$H = \frac{\hbar^2}{2m}\left(k_x - \frac{eB_{||}z}{\hbar}\right)^2 + \frac{\hbar^2 k_y^2}{2m} - \frac{\hbar^2}{2m}\frac{d^2}{dz^2} + V(z)$$

Correlation of the electron motion in z and x directions !!!
(variables x and z are not separable)

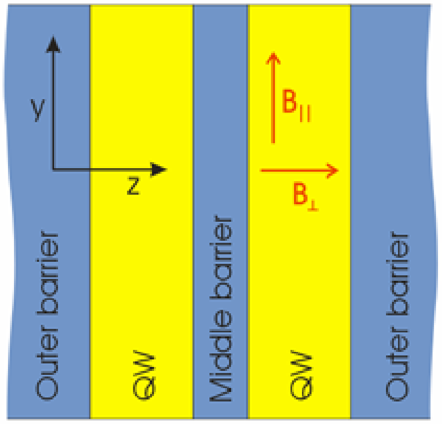
Energy spectrum:

$$E_n(k_x,k_y) = E_n(k_x) + \frac{\hbar^2 k_y^2}{2m}$$

Non-parabolic electron dispersion

In-plane magnetic field:

$$\mathbf{B} = (0, B_{||}, 0)$$
$$\mathbf{A} = (B_{||}z, 0, 0)$$



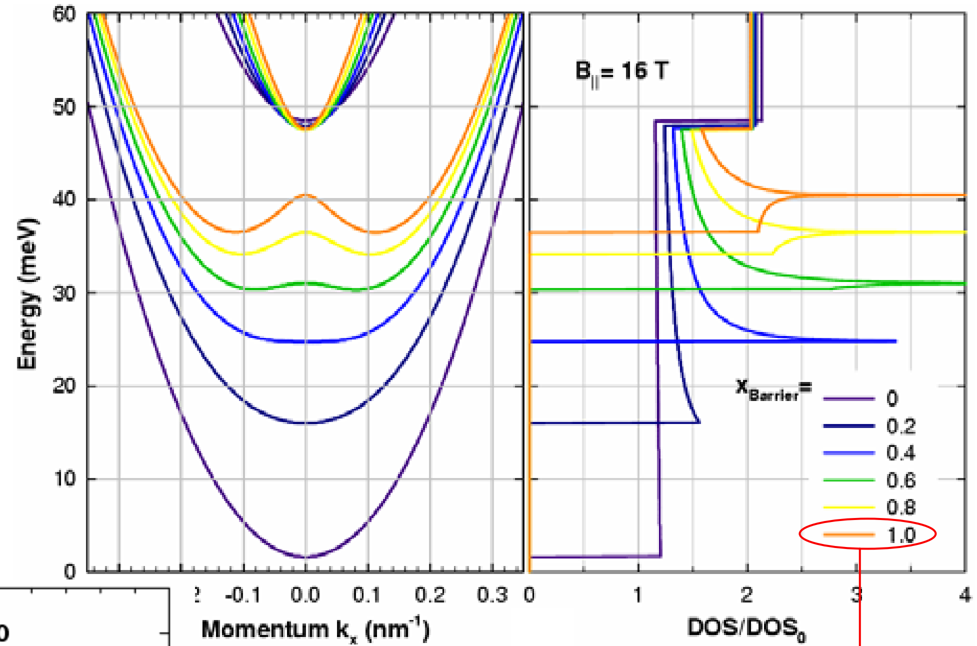
Quasi-classical interpretation:

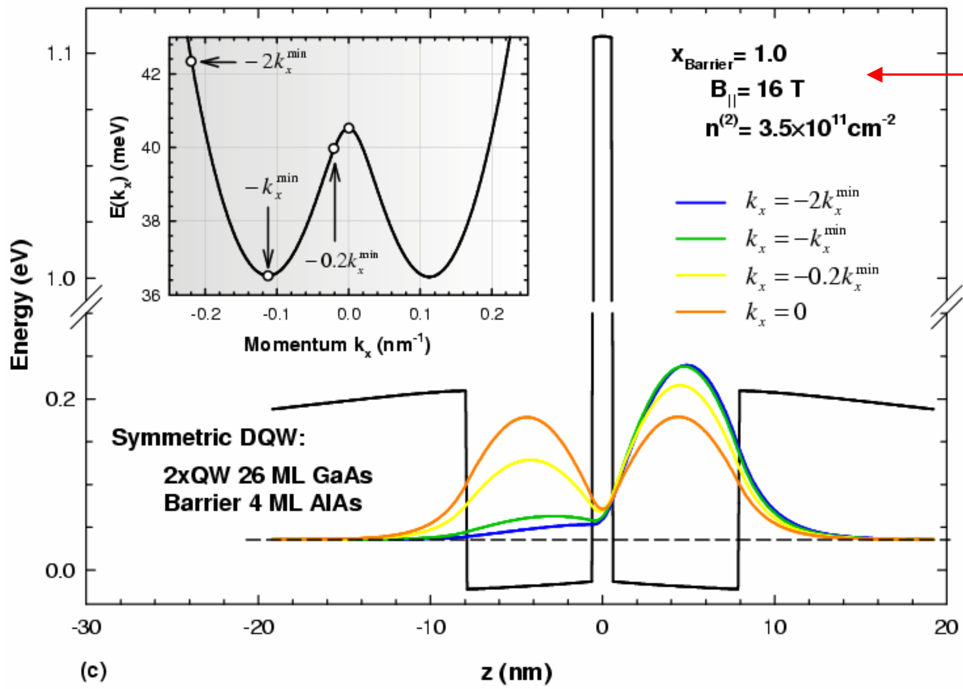
Lorentzian force acts in the direction perpendicular to its velocity and magnetic field

DQW subject to in-plane magnetic fields

DQW in in-plane magnetic fields

Strong modification of electron dispersion, density of states and wave functions induced by the in-plane magnetic field





Logarithmic singularity in DOS induced by $B_{\|}$

Electrons become localized either in the left or in the right well

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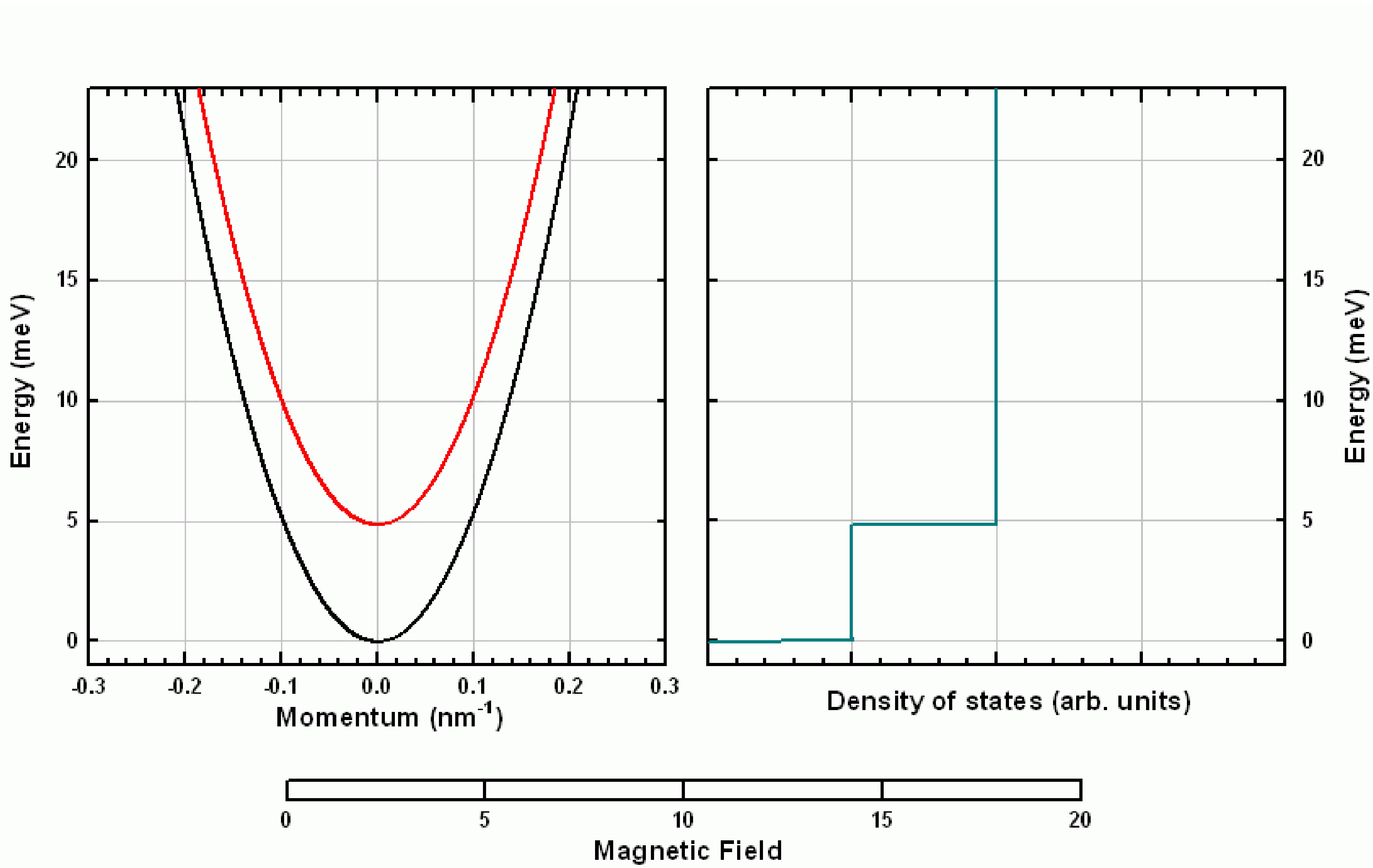
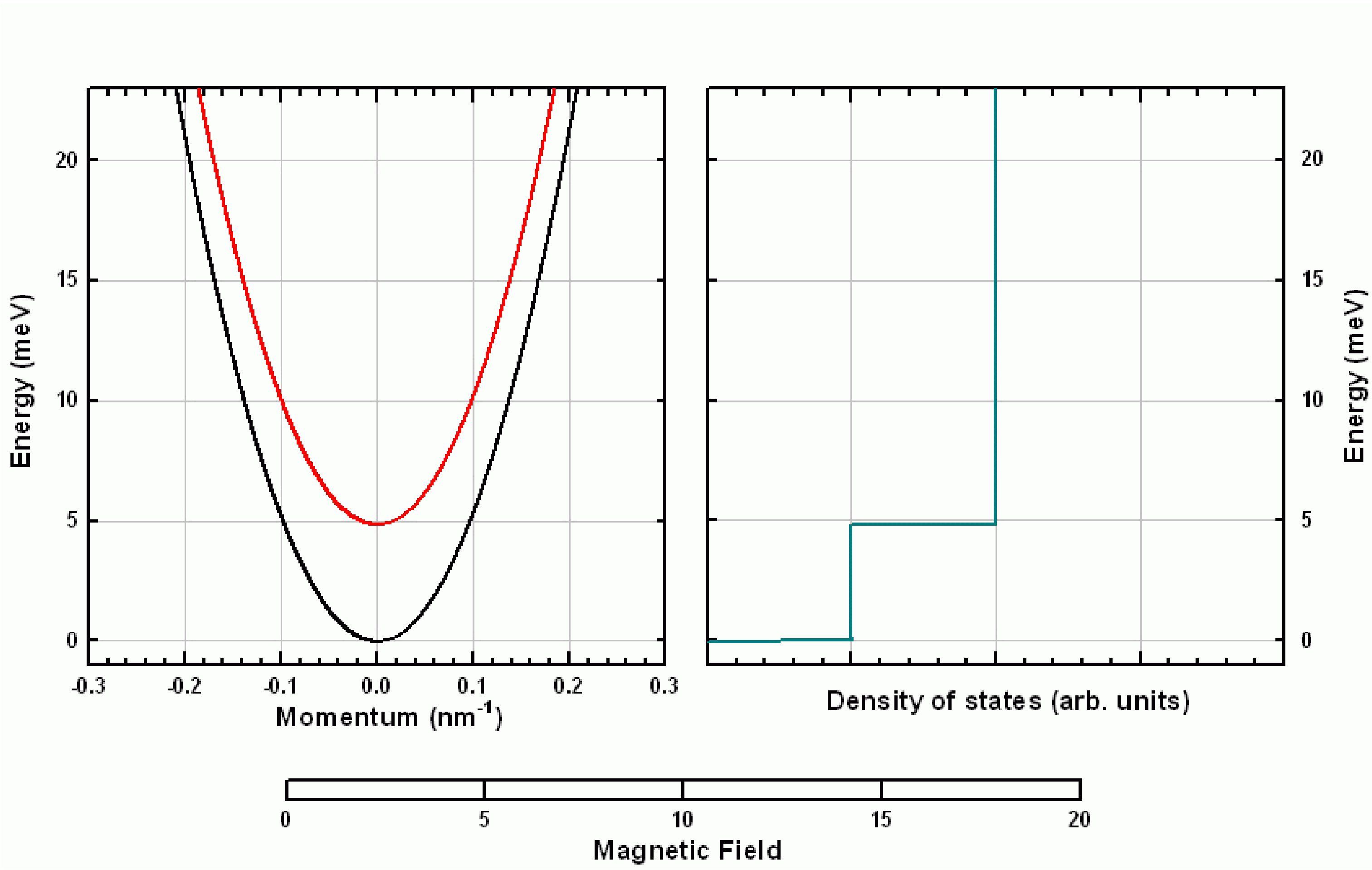
In-plane-magnetic-field induced transition of the system

single-layer ⟶ bilayer

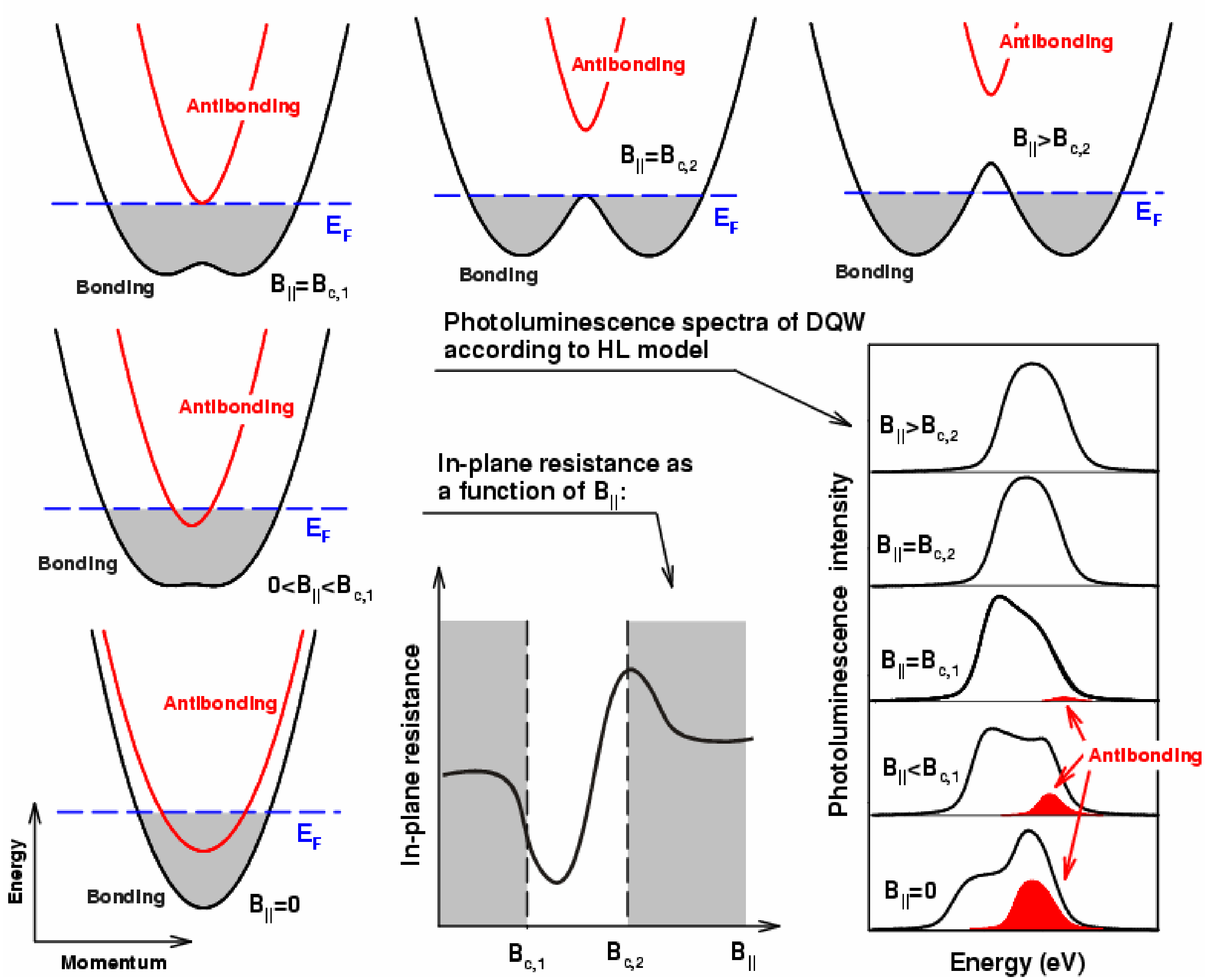
DQW in in-plane magnetic fields



DQW in in-plane magnetic fields



2D electron gas in double quantum well



Simmons et al., Phys. Rev. Lett. 73, 2256 (1994) Huang and Lyo, Phys. Rev. B 59, 7600 (1999)

2D electron gas in double quantum well

Transport properties…..

$B_{\|}$-induced modification of density of states at the Fermi level

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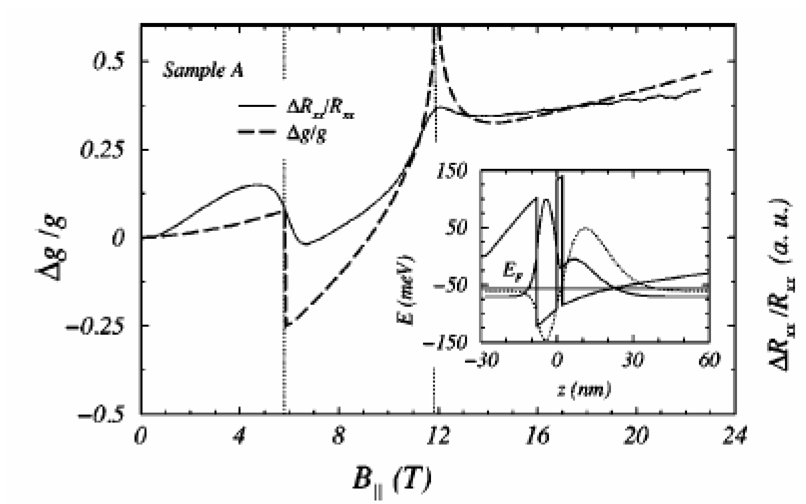
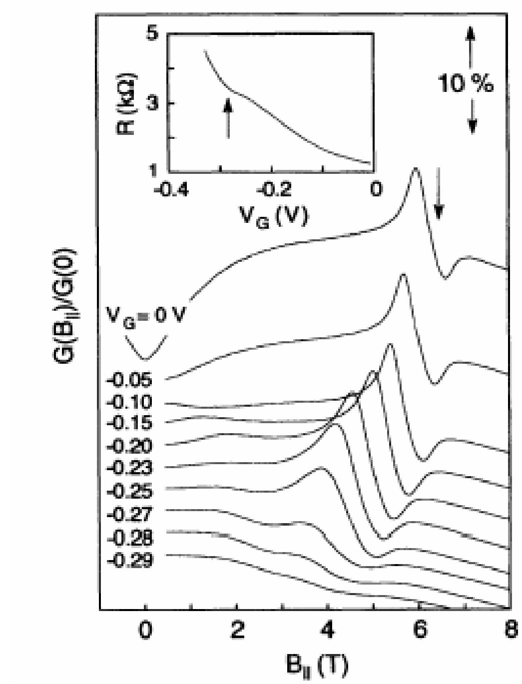
Modulation of the in-plane conductance of DQW



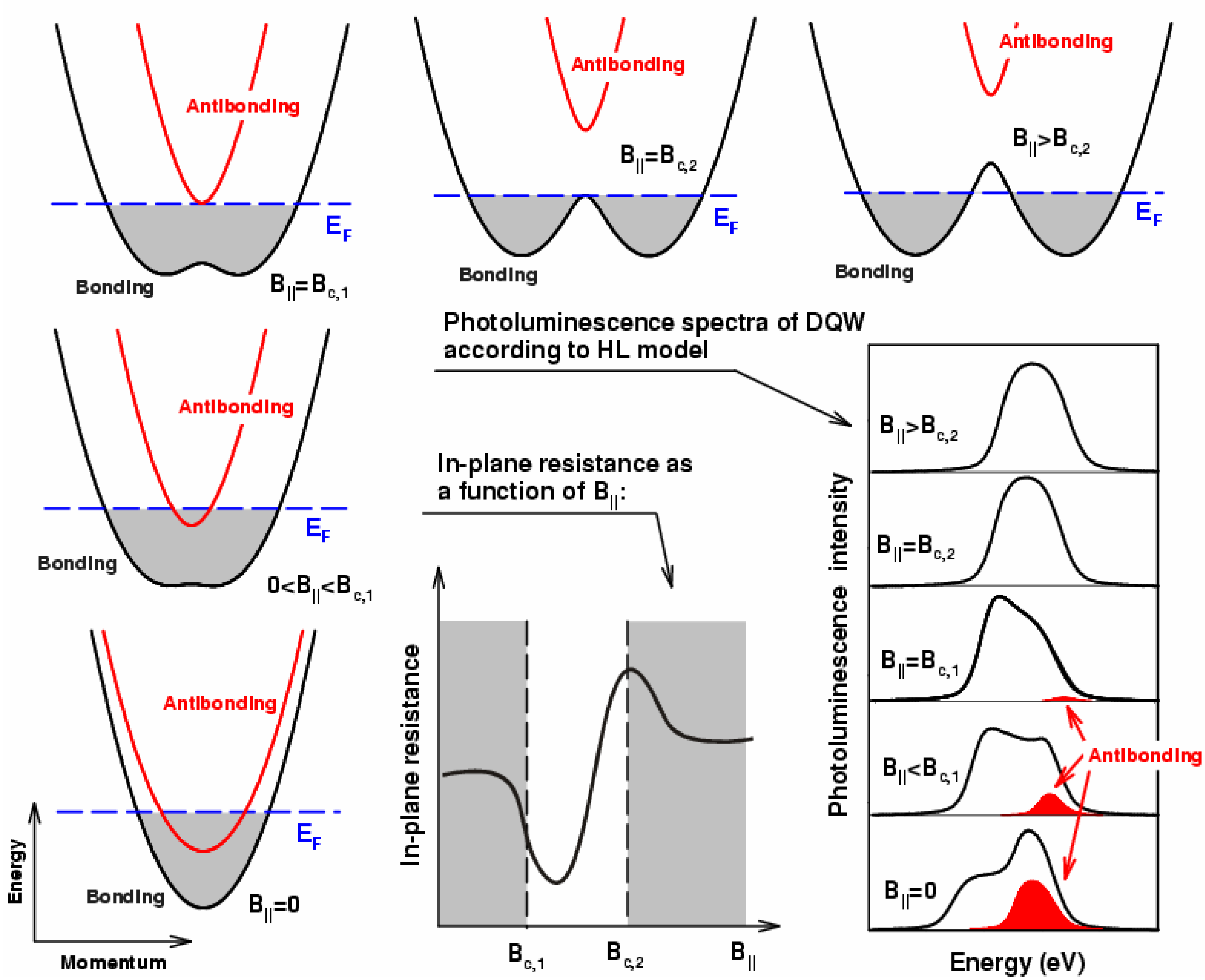
O. N. Makarovskii et al., Phys. Rev. B 62, 10 908 (2000)



J. A. Simmons et al., Phys. Rev. Lett. 73, 2256 (1994)

Optical experiments?

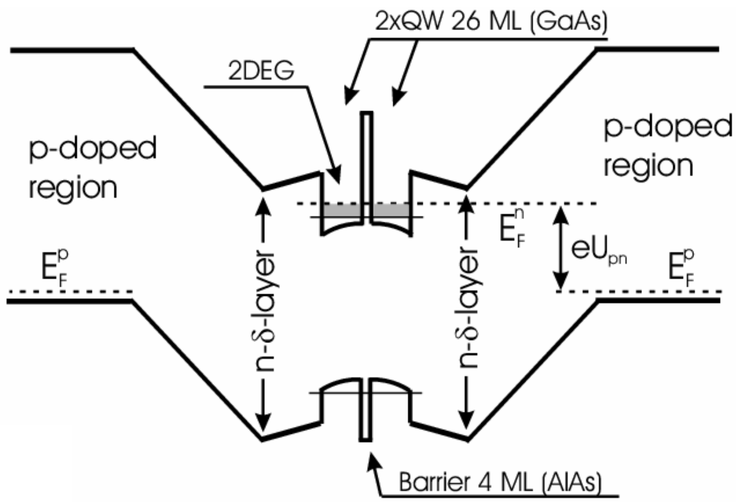
2D electron gas in double quantum well



Simmons et al., Phys. Rev. Lett. 73, 2256 (1994) Huang and Lyo, Phys. Rev. B 59, 7600 (1999)

2D electron gas in double quantum well

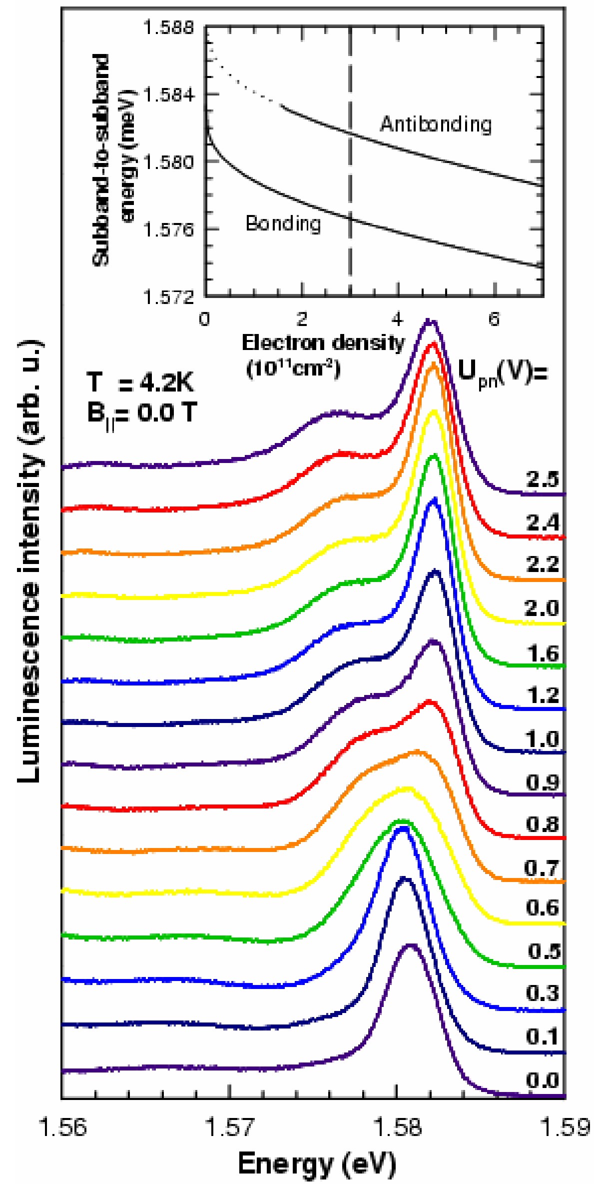
Band profile of the sample:



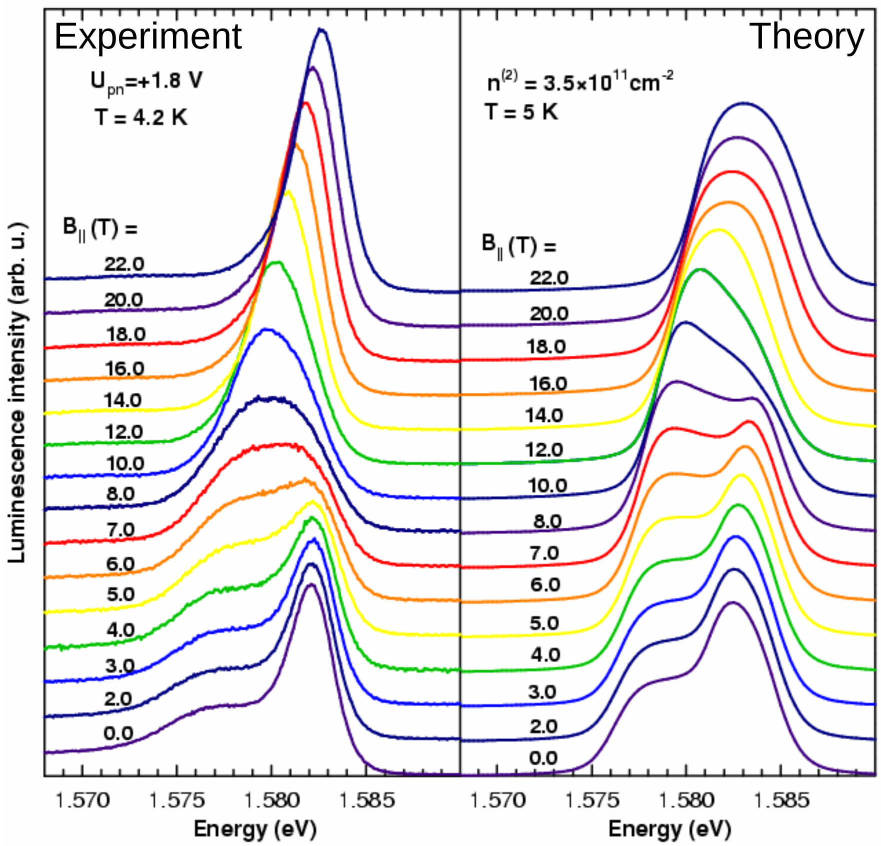
Photoluminescence (PL):

2D electron density variable by the applied bias

Exciton-like PL transforms into free electron-hole recombination at higher densities

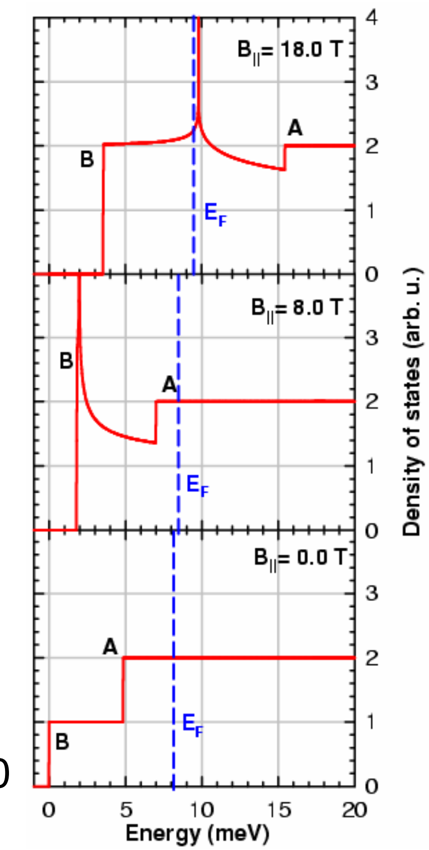


2D electron gas in double quantum well



Electron density of states:

1. Depopulation of antibonding subband clearly visible v PL spectra
2. Good agreement with a relatively simple theory
3. Theoretical model (without exciton effects) suggested after Huang and Lyo, PRB 59, 7600 (1999)

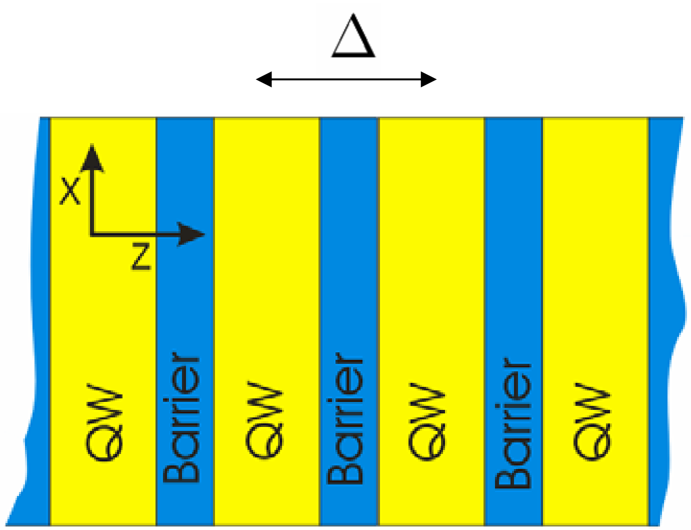


Effects in 2DEG induced by in-plane magnetic field observable in optical (PL) experiment…..

Orlita et al. Phys. Rev. B 72, 165314 (2005)

Bloch oscillations in superlattices

Semiconductor superlattice = system with 1D periodicity



Hamiltonian

$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{p_z^2}{2m} + V(z)$$

Periodic potential

$$V(z) = V(z + \Delta)$$

$$\Delta \sim 10 \text{ nm}$$

Bloch theorem

$$\psi_{k_z}(z + \Delta) = e^{ik_z \Delta} \psi_{k_z}(z)$$

Energy spectrum:

$$E(\vec{k}) = E(k_z) + \frac{\hbar^2 (k_y^2 + k_x^2)}{2m}$$

1D band structure

$$E(k_z) = E(k_z + 2\pi/\Delta)$$

L. Esaki and R. Tsu, IBM J. Res. Dev. 14, 61 (1970)

Bloch oscillations in superlattices

Quasi-classical treatment:

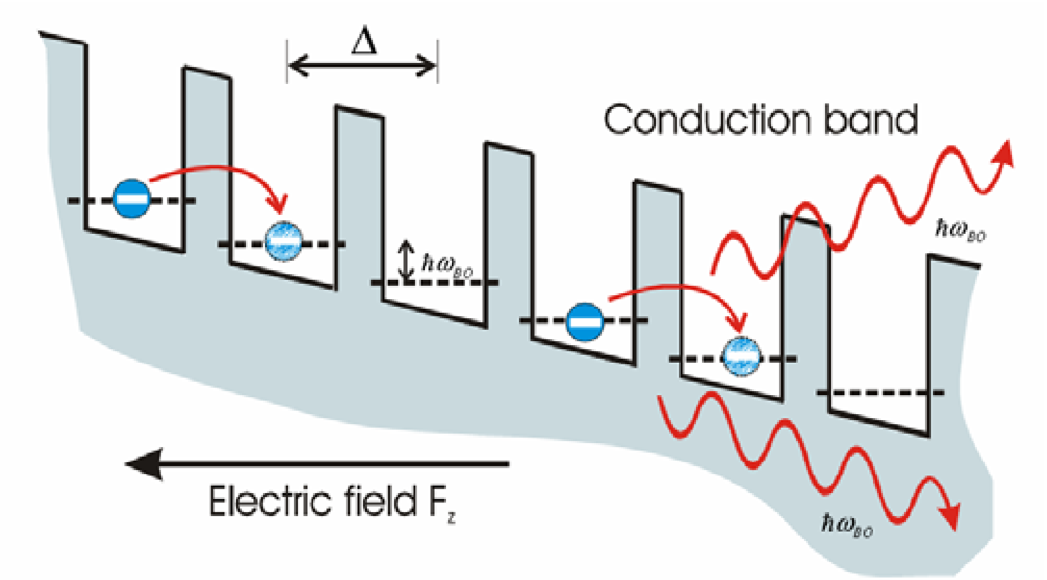
$$\hbar \dot{k}_z = eF_z$$

$$v_z = \frac{1}{\hbar}\frac{dE(k_z)}{dk_z}$$

Quantum-mechanical description:

$$H(k_z) = E(k_z) - \hat{\imath}eF_z\frac{d}{dk_z}$$

$$E_n = \frac{2\pi}{\Delta}\int_0^{2\pi/\Delta} E(k_z)dk_z + n\hbar\omega_{BO}$$



Quasi-stationary discrete states, so-called Wannier-Stark ladder

$$\hbar\omega_{BO} = eF_z\Delta$$

SL = possible source of THz radiation

Superlattice subject to in-plane magnetic fields

Hamiltonian of superlattice in in-plane magnetic field:

$$H = \frac{\hbar^2}{2m}\left(k_x - \frac{eB_{||}z}{\hbar}\right)^2 + \frac{\hbar^2 k_y^2}{2m} - \frac{\hbar^2}{2m}\frac{d^2}{dz^2} + V(z)$$

Energy spectrum:

$$E_n(k_x, k_y) = E_n(k_x) + \frac{\hbar^2 k_y^2}{2m}$$

Symmetry of Hamiltonian induced by magnetic field:

$$K_0 = \frac{eB_{||}\Delta}{\hbar}$$

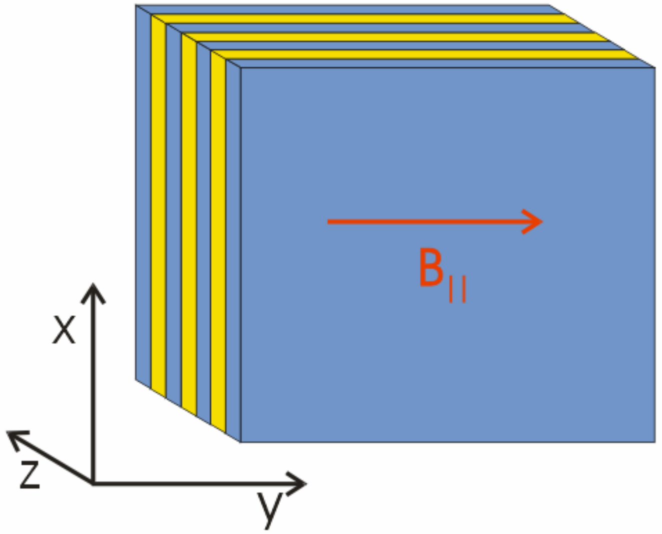
$$H(z, k_x) = H(z - \Delta, k_x + K_0)$$

$$\Downarrow$$

$$E_n(k_x) = E_n(k_x + K_0)$$

In-plane magnetic field:

$$\mathbf{B} = (0, B_{||}, 0)$$
$$\mathbf{A} = (B_{||}z, 0, 0)$$



Superlattice subject to in-plane magnetic fields

$$E_n(k_x) = E_n(k_x + K_0)$$

Calculated on the basis of the simple tight-binding model

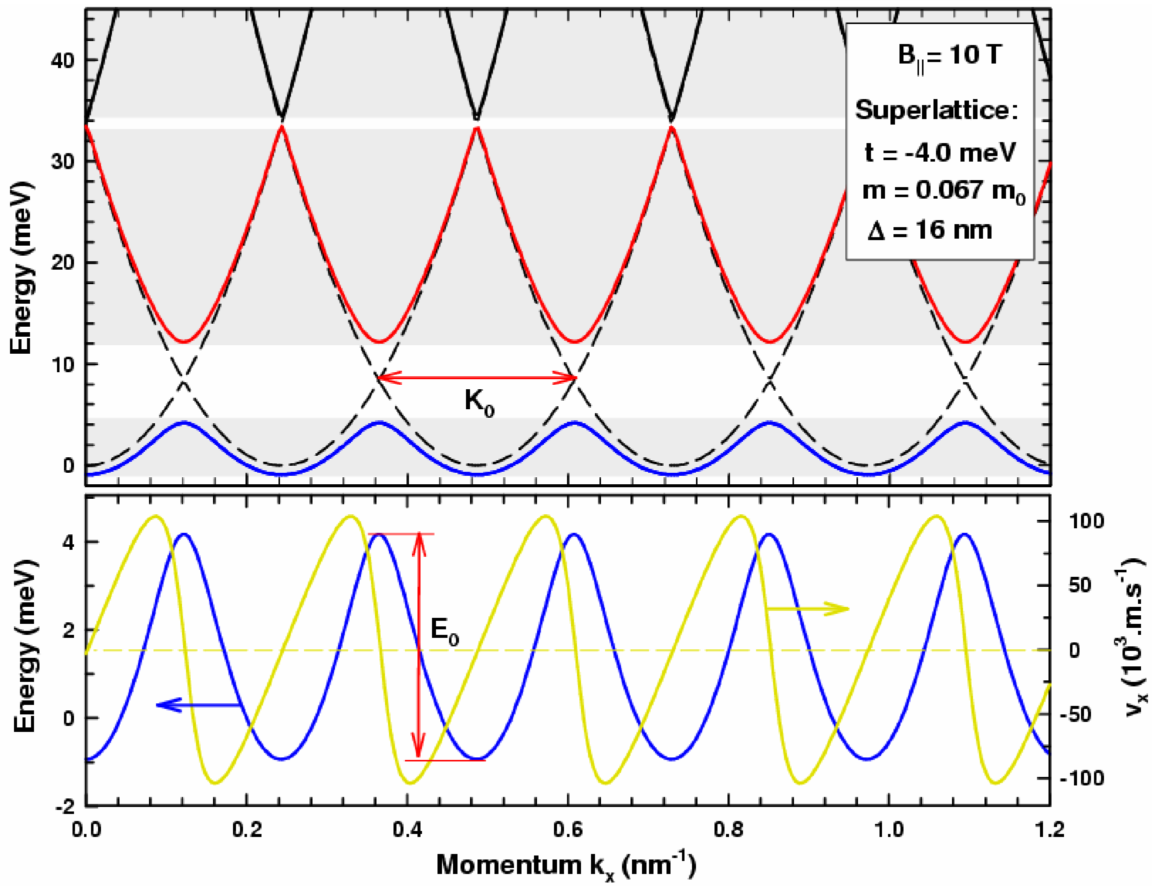
$n = 1, 2, 3$

Periodical band structure induced by the in-plane magnetic field

Brillouin zone size and miniband width tunable by the magnetic field

$$K_0 = \frac{eB_{||}\Delta}{\hbar}$$

$$E_0 \approx \frac{e^2 B_{||}^2 \Delta^2}{8m}$$



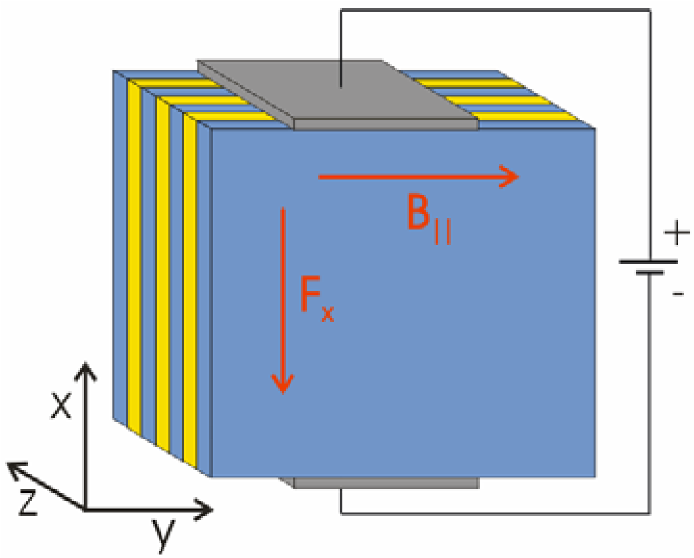
Superlattice subject to in-plane magnetic fields

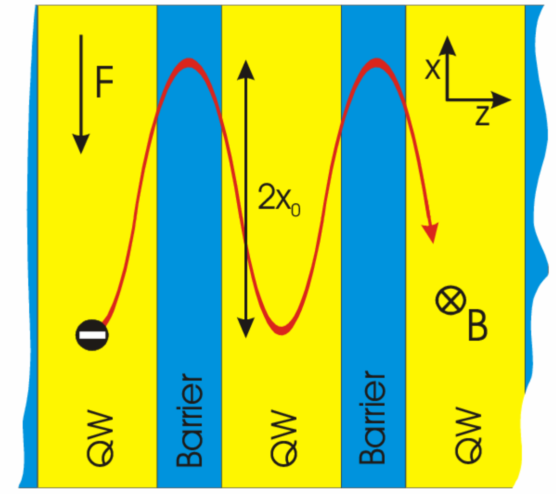
Quasi-classical description:

$$\hbar \dot{k}_x = eF_x$$

$$k_x(t) = k_x^0 - \frac{eF_x}{\hbar} t$$

$$v_x(t) = v_x(t + 2\pi/\omega_{B_{||}})$$





Oscillation frequency:

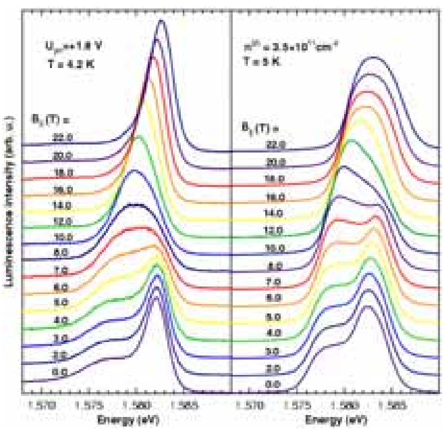
$$\omega_{B_{||}} = \frac{2\pi}{\Delta} \frac{F_x}{B_{||}}$$

Classical drift motion in crossed magnetic and electric fields: $F_x/B_{||}$

Tunable emittor of THz radiation?

Summary

Magneto-optical laboratory MFF UK in cooperation with GHMFL allows a wide range of optical experiments in high magnetic fields



The optical properties of 2D structures are investigated. The main emphasis is put on effects induced by the in-plane magnetic field

Prediction of novel terahertz oscillations in superlattices controlled by the magnetic field