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

Other materials: In$_x$Ga$_{1-x}$As/GaAs
Cd$_x$Zn$_{1-x}$Te/CdTe
Cd$_x$Mn$_{1-x}$Te/CdTe...

Preparation: Mostly MBE
Physics of quantum wells

Basic quantum mechanics…..

Hamiltonian:
\[ H = \frac{p_x^2}{2m} + \frac{p_y^2}{2m} + \frac{p_z^2}{2m} + V(z) \]

\[ \Rightarrow E_i(k_x, k_y) = E_i + \frac{\hbar^2 k_x^2 + \hbar^2 k_y^2}{2m} \]

Energy spectrum:

Double quantum well (DQW):

Discrete subband energy

Free motion in QW plane

Constant density of states (DOS):

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

DQW = the simplest 3D system
Magneto-optical laboratory MFF UK

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.....)

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)
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:

\[ \psi_{n,k_x,k_y}(x, y, z) = e^{i(k_xx + k_yy)} \chi_{n,k_x}(z) \]

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

\[ H = \frac{\hbar^2}{2m} \left( k_x - \frac{eB_x}{\hbar} \right)^2 + \frac{\hbar^2 k_y^2}{2m} - \frac{\hbar^2}{2m} \frac{d^2}{dz^2} + V(z) \]

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

Energy spectrum:

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

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 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

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

single-layer $\rightarrow$ bilayer
DQW in in-plane magnetic fields

![Graph showing energy vs. momentum and density of states under in-plane magnetic fields.](image-url)
DQW in in-plane magnetic fields

![Graph showing DQW in in-plane magnetic fields]

- Energy (meV) vs. Momentum (nm\(^{-1}\))
- Density of states (arb. units) vs. Magnetic Field

DQW subject to in-plane magnetic fields
2D electron gas in double quantum well

Photoluminescence spectra of DQW according to HL model

In-plane resistance as a function of $B_{||}$:

Simmons et al., Phys. Rev. Lett. 73, 2256 (1994)  
2D electron gas in double quantum well

B\textsubscript{∥}-induced modification of density of states at the Fermi level

Modulation of the in-plane conductance of DQW

Transport properties.....

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

Optical experiments?

2D electron gas in double quantum well

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

1. Depopulation of antibonding subband clearly visible in 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)

Bloch oscillations in superlattices

Semiconductor superlattice = system with 1D periodicity

Hamiltonian

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

Periodic potential

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

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

Bloch theorem

$$\psi_{kz}(z + \Delta) = e^{ik\Delta} \psi_{kz}(z)$$

Energy spectrum:

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

1D band structure

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

Quasi-classical treatment: Quantum-mechanical description:

\[ \hbar k'_z = e F_z \]

\[ \nu_z = \frac{1}{\hbar} \frac{dE(k_z)}{dk_z} \]

\[ H(k_z) = E(k_z) - \hat{e} F_z \frac{d}{dk_z} \]

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

Bloch oscillations in superlattices

SL = possible source of THz radiation

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

\[ \hbar\omega_{BO} = e F_z \Delta \]
Superlattice subject to in-plane magnetic fields

Hamiltonian of superlattice in in-plane magnetic field:

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

Energy spectrum:

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

In-plane magnetic field:

\[ B = (0, B_\parallel, 0) \]
\[ A = (B_\parallel z, 0, 0) \]

Symmetry of Hamiltonian induced by magnetic field:

\[ K_0 = \frac{eB_\parallel \Delta}{\hbar} \]

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

\[ E_n(k_x) = E_n(k_x + K_0) \]
Superlattice subject to in-plane magnetic fields

Periodical band structure induced by the in-plane magnetic field

Brillouin zone size and miniband width tunable by the magnetic field

\[ E_n(k_x) = E_n(k_x + K_0) \]

Calculated on the basis of the simple tight-binding model

\[ n = 1, 2, 3 \]

\[ K_0 = \frac{e B_{||} \Delta}{\hbar} \]

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

Superlattice subject to in-plane magnetic fields

- \( B_{||} = 10 \text{T} \)
- Superlattice:
  - \( t = -4.0 \text{ meV} \)
  - \( m = 0.067 m_0 \)
  - \( \Delta = 16 \text{ nm} \)
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:

\[ \omega_{B||} = \frac{2\pi F_x}{\Delta B_{||}} \]

Classical drift motion in crossed magnetic and electric fields:

\[ F_x/B_{||} \]

Tunable emitter 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.