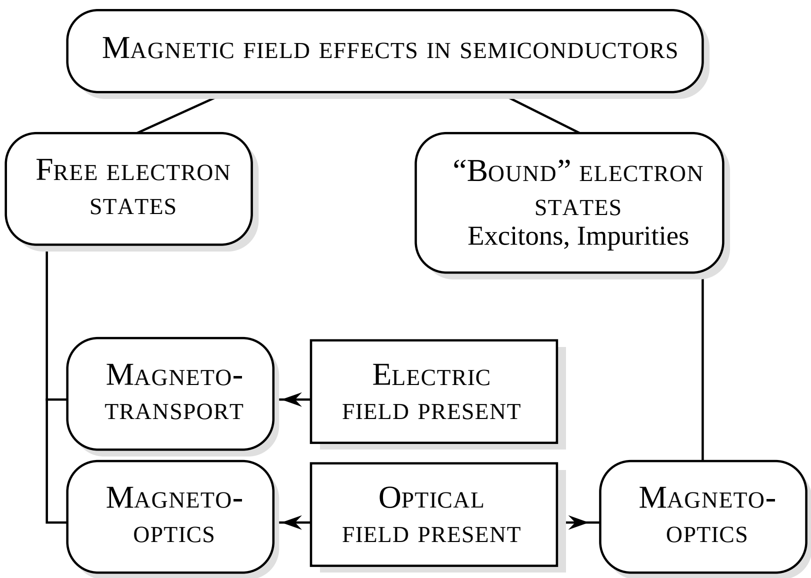
Chapter 11

SEMICONDUCTOR IN MAGNETIC FIELDS

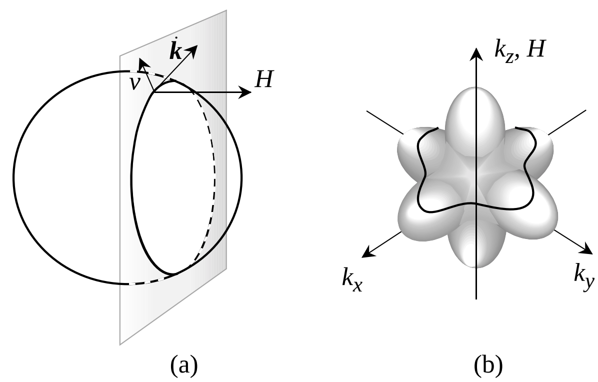

MAGNETIC FIELD EFFECTS IN SEMICONDUCTORS
FREE ELECTRON STATES
"BOUND" ELECTRON STATES
Excitons, Impurities
MAGNETO-TRANSPORT
ELECTRIC FIELD PRESENT
MAGNETO-OPTICS
OPTICAL FIELD PRESENT
MAGNETO-OPTICS

CYCLOTRON RESONANCE

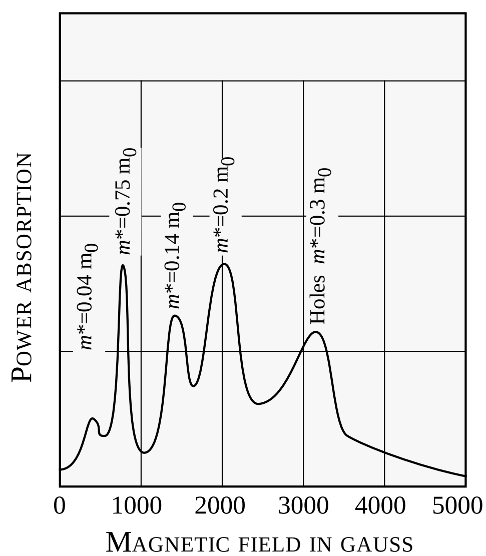
At low magnetic field the electron bandstructure is unaffected

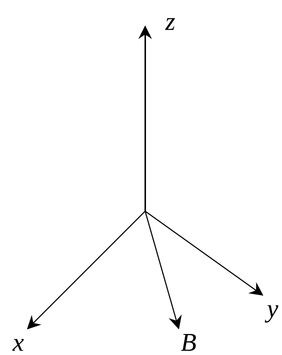
➡ electron orbits the constant energy surface with the cyclotron frequency

$$\omega_c = \frac{eB}{m^*}$$



(a) Schematic showing the orbit of an electron in a magnetic field. The electron moves on a constant energy surface in a plane perpendicular to the magnetic field.
(b) Orbit of an electron (or hole) on a constant energy surface that is anisotropic.





Results of cyclotron resonance absorption in germanium at 4 K, at 24 GHz. The static magnetic field is in a (110) plane at 60° from a (100) axis. Both electrons and holes are produced by illumination. The peaks correspond to the cyclotron frequency coinciding with 24 GHz. (Adapted from G. Dresselhaus, A.F. Kip, and C. Kittel, *Physical Review*, Vol. 98, 368 (1955).)

SEMICLASSICAL THEORY OF MAGNETOTRANSPORT

In Hall effect it is possible to measure:

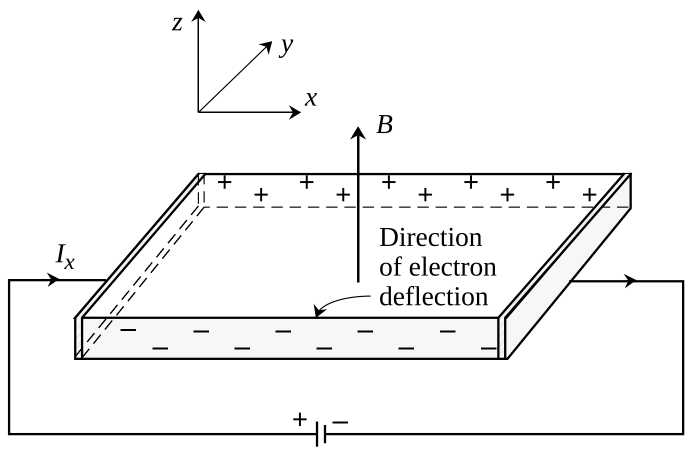
Hall coefficient: $R_H = \dfrac{F_y}{J_x B} = -\dfrac{1}{ne}$ n-type

$= \dfrac{1}{pe}$ p-type

Magneto-resistance: $\rho_H = \dfrac{F_x}{J_x}$

Hall mobility: $= \dfrac{R_H}{\rho_H} = \mu_H = r_H \cdot \mu$

r_H = Hall factor

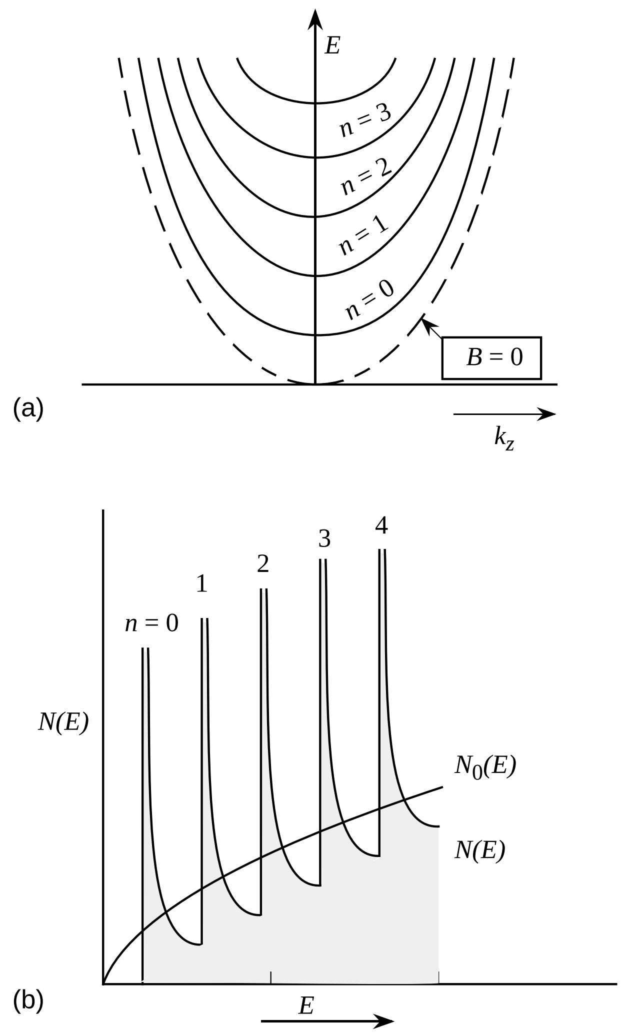


A rectangular Hall sample of an n-type semiconductor.

ELECTRONS IN STRONG MAGENTIC FIELDS: LANDAU LEVELS

At high magnetic fields the bandstructure of electrons is altered

3 Dimensions: $E = \left(n + \frac{1}{2}\right)\hbar\omega_c + \frac{\hbar^2}{2m^*} k_z^2$

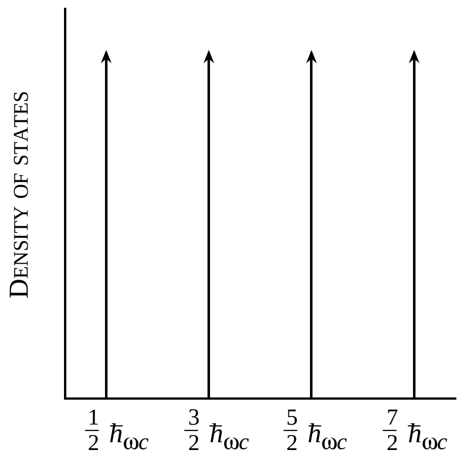


(a) Effect of magnetic field on the bandstructure of a semiconductor. Only k_z is a good quantum number. The magnetic field produces quantization in the x-y plane leading to Landau levels. The dashed curve is for zero field.
(b) Density of staes in a 3D system in the presence of a magnetic field. The density of states develops singularities due to quantization in the plane perpendicular to the magnetic field. Also shown is the zero field density of states for comparison.

LANDAU LEVELS IN 2-DIMENSIONS

A singular density of states is produced:

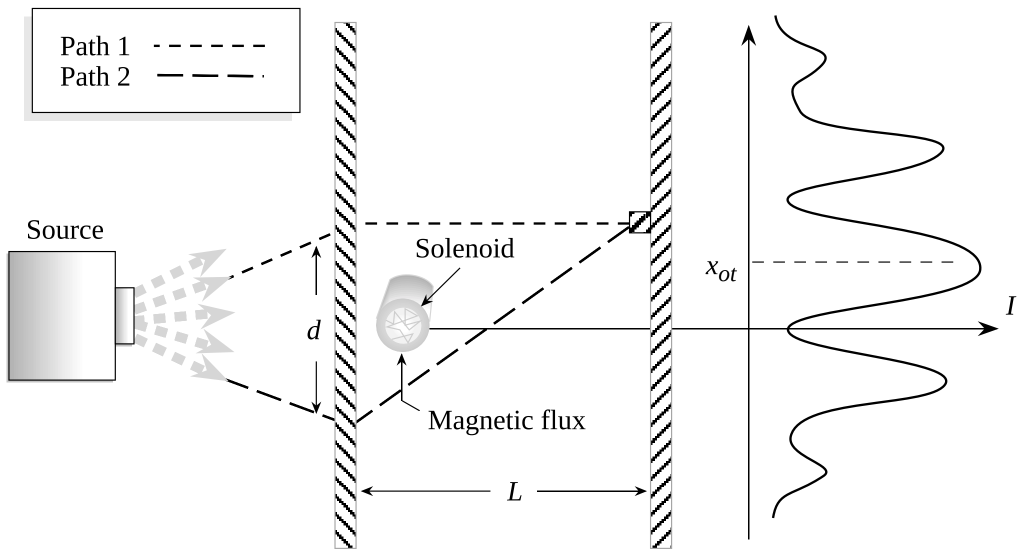
$$E_{nl} = E_n + \left(l + \frac{1}{2}\right) \hbar \, \frac{eB_z}{m_{||}}$$



Singular density of states in an ideal 2D system in the presence of a magnetic field.

AHARONOV-BOHM EFFECT: QUANTUM INTERFERENCE

$$\text{Current} \propto \cos\frac{e\phi}{\hbar} \; ; \; \Phi = B \cdot A$$



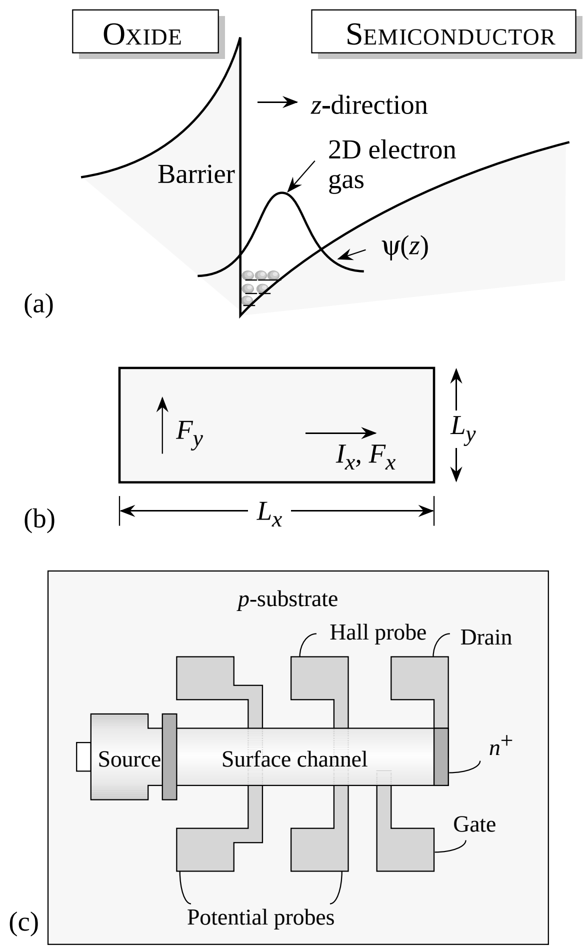
A magnetic field can influence the motion of electrons even though it exists only in regions where there is an arbitrarily small probability of finding the electrons. The interference pattern of the electrons can be shifted by altering the magnetic field.

QUANTUM HALL EFFECT

Hall effect measurement at low temperature in 2D systems where scattering time is very long, compared to 1/cyclotron frequency

➡ $\omega_c \tau >> 1$

$$\sigma_{xx} \rightarrow 0; \sigma_{xy} = -\frac{ne}{B}$$

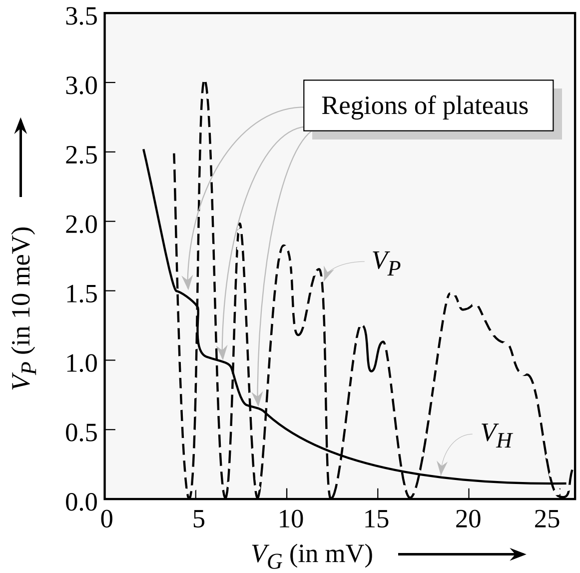


(a) Band profile and the location of the 2D electron gas used for quantum Hall effect experiments. (b) The applied electric field and drift current orientation. (c) A schematic of the positions of the various contacts used for quantum Hall effect.

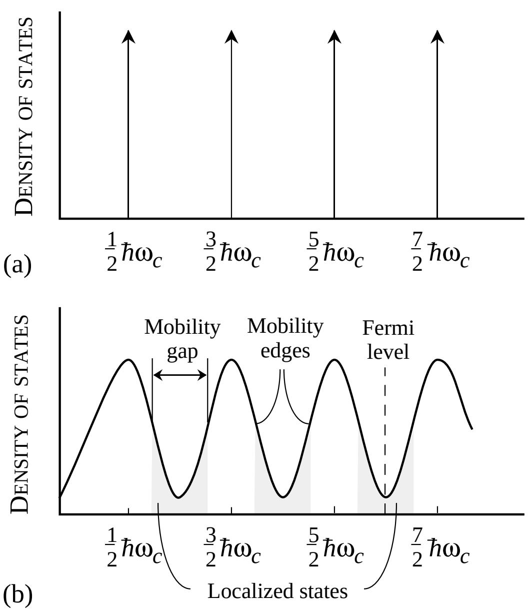
QUANTUM HALL EFFECT

Hall resistivity is found to have plateaus.

Results from the original quantum Hall effect carried out by K. von Klitzing, G. Dorda, and M. Pepper. A magnetic field of 18 T is perpendicular to the sample and measurements area done at 1.5 K. A constant current of 1 μA is forced to flow between the source and the drain.
(After K. von Klitzing, G. Dorda, and M. Pepper, *Phys. Rev. Lett.*, **45**, 494 (1980).)



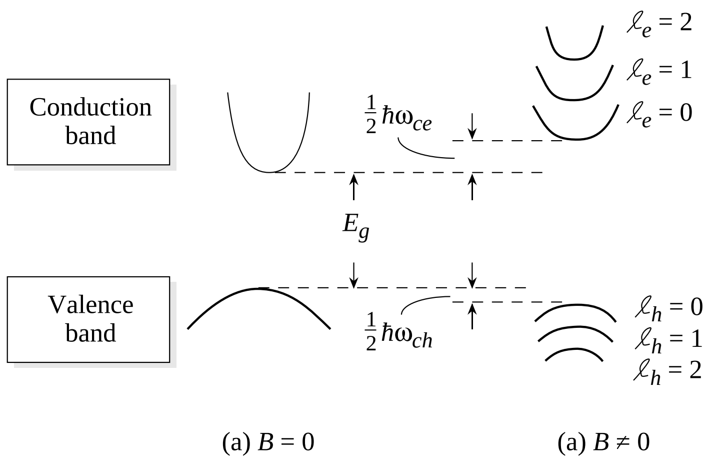
Localized states may be the source of plateaus.



A schematic of the density of states in a 2-dimensional electron system in the presence of a high magnetic field. Case (a) is for an ideal system, while case (b) is for a real system with some disorder.

MAGNETO-OPTIC STUDIES

A magnetic field causes splitting of the electron and hole bands into Landau levels. Optical transitions can reveal bandstructure properties.



(a) Bands in a semiconductor in the absence of a magentic field.
(b) Bandstructure in the presence of a magnetic field.

Transition energies:

$$E_{mo} = E_g + \frac{\hbar^2 kz^2}{2\mu} + (\rho + 1/2)\hbar\omega_{ceh}$$

$$\omega_{ceh} = \frac{eB}{\mu}$$

μ = e-h reduced mass