

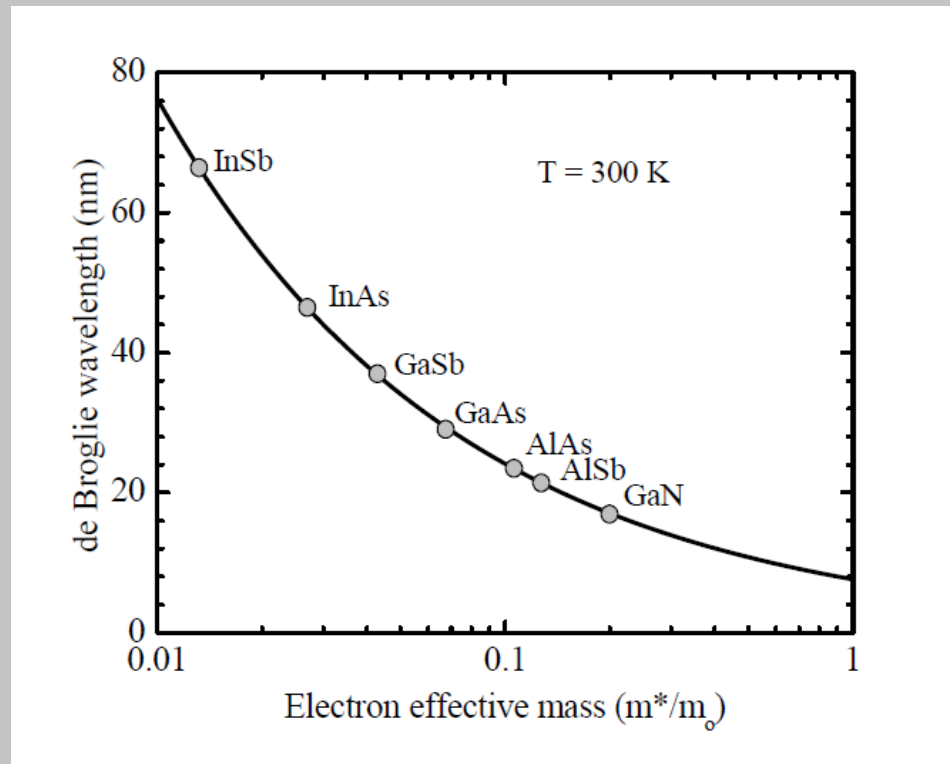
02 Elektrische und Transporteigenschaften

- Einleitung
- Hall-Effekt
- Quantum-Hall und Shubnikov-de Haas-effekt
- Ladungsträgertransport in Volumenmaterial
- Boltzmann Transportgleichung
- Streumechanismen im 3-dim. System
- Streumechanismen im 2-dim. Systemen
- Kohärenz und Mesoskopische Systeme

Einleitung

De Broglie Wellenlänge

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m^*E}} = \lambda_0 \sqrt{\frac{m_0}{m^*}}$$



Einleitung

De Broglie Wellenlänge λ

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m^*E}} = \lambda_0 \sqrt{\frac{m_0}{m^*}},$$

Mittlere freie Weglänge l_e

In elastic scattering, the motion of the electron remains coherent. The time, τ_e , between two successive elastic collisions is called *the mean free time* and can be used to define the mean free path, l_e , between scattering events, such that $l_e = \tau_e v$, where v is the electron group velocity ($v = p/m$). The wave-like properties of the electrons are coherent when they travel a distance l_e .

Inelastische Streulänge:

Generally speaking, l_i is larger than l_e , which means that the electrons undergo several collisions before losing their energy. The inelastic scattering length can be written as $l_i = \sqrt{D\tau_i}$, where τ_i is the time between inelastic collisions, D is the diffusion coefficient given by $D = v^2\tau_e/\alpha$, and $\alpha = 3$ for bulk, $\alpha = 2$ for quantum wells, and $\alpha = 1$ for quantum wires.

Thermische Diffusionslänge l_T

$$l_T = \sqrt{D\tau_T} = \sqrt{D/(k_B T)}.$$

$$\tau_T = \hbar/(k_B T).$$

This length is the distance that electrons travel before their quantum coherence is destroyed. The thermal dephasing of electrons occurs for both elastic and inelastic scattering.

Koheränzlänge

The coherence length, l_ϕ , is thus determined by the smaller value of either the inelastic scattering length or the thermal diffusion length. The coherence length defines the limit below which the electrons have wavelike characteristics.

Mesoskopische Systeme:

which are characterized by physical dimensions smaller than the coherence length.

Transportregime

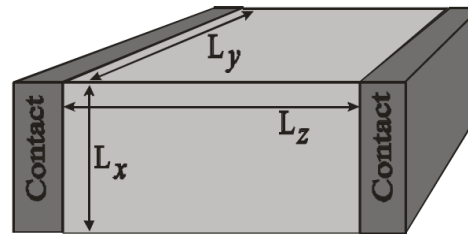
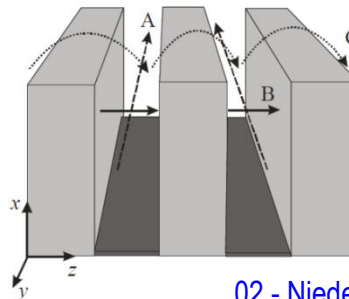


TABLE 5.1 The Transport Regimes in Semiconductor Devices in Terms of the Device Dimensions

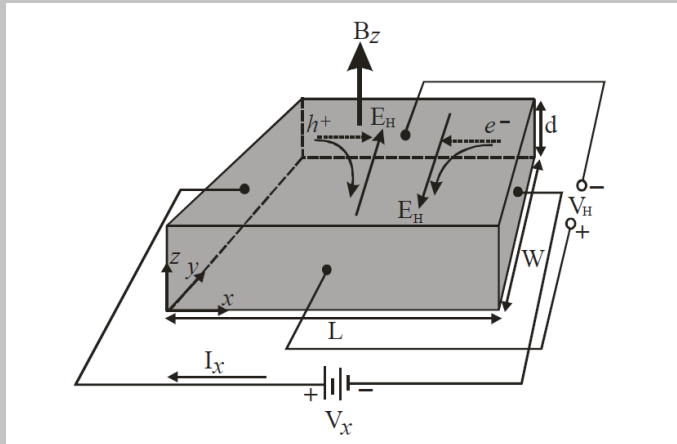
Quantum regime	L_z is comparable with the electron wavelength. ($L_z \sim \lambda$)
Mesoscopic regime	$L_z \leq l_\varphi$, where l_φ is coherence length, which is also known as the dephasing length
Classical regime	$L_z > l_\varphi$
Classical ballistic regime	The mean free path of elastic collisions is larger than L_z ($l_e \geq L_z$)
Classical transverse size effect	<ul style="list-style-type: none"> • Effects related to the mean free path: both L_x and L_y are of the order of l_e. • Effects related to diffusion: both L_x and L_y are of the order of l_i, where l_i is the inelastic scattering length.

The wavelength, λ , is taken as the de Broglie wavelength and the interconnect distance is L_z .



Hall-Effekt

Hall-Bar Geometrie:



Lorentz-Kraft:

$$q \cdot E_y + q \cdot v_x \cdot B = 0$$

$$v_D = v_x = \mu_p \cdot E_x$$

$$j_x = \sigma \cdot E_x$$

$$\sigma = q \cdot \mu \cdot p$$

$$E_y = -\mu_p \cdot E_x \cdot B = -1/(qp) \cdot j_x \cdot B = -R_H \cdot j_x \cdot B$$

$$R_H = (q \cdot p)^{-1} \quad \text{Hall-Konstante}$$

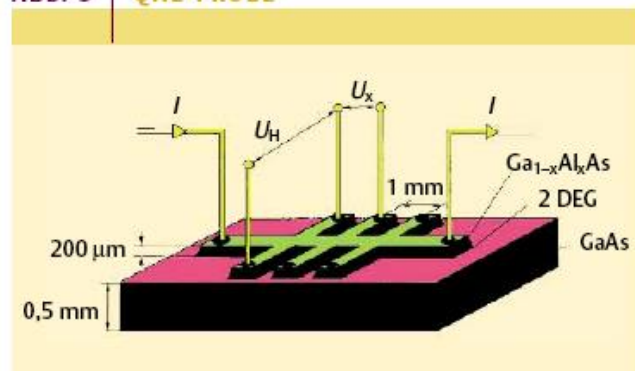
$$U_H = -E_y \cdot W = R_H \cdot (I_x / H) \cdot B \quad \text{Hall-Spannung}$$

$$\mu_H = E_y / (E_x \cdot B) \quad \text{Hall-Beweglichkeit}$$

für Elektronen und Löcher (2-Band-Modell)

$$R_H = \frac{1}{q} \cdot \frac{p\mu_p^2 - n\mu_n^2}{(p\mu_p + n\mu_n)}$$

ABB. 3 QHE-PROBE



Schema einer QHE-Probe zur Messung der Hall-Spannung U_H und der Längsspannung U_x .

Hall-Effekt

Freie Ladungsträgerkonzentration

$$n_H = -\frac{I_x B_z}{e V_H d}$$

Hall-Beweglichkeit

$$\mu_n = \frac{I_x L}{e V_x n_H W d} = \frac{GL}{e n_H W d}$$

Hall-Koeffizient

$$R_H = \frac{r \mathcal{E}_y}{J_x B_z} = -\frac{r}{n_H e}$$

Hall-faktor

$$r = \frac{\langle \tau^2 \rangle}{\langle \tau \rangle^2}$$

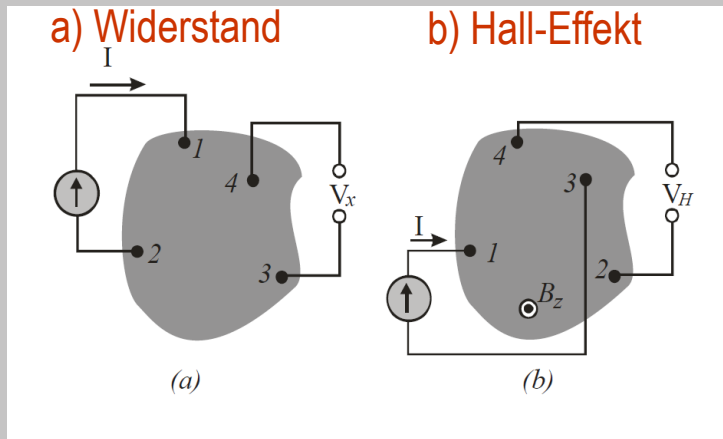
$$\mu_H = \frac{\langle \tau^2 \rangle}{\langle \tau \rangle^2} \mu$$

für Elektronen und Löcher (2-Band-Modell)

$$R_H = \frac{1}{q} \cdot \frac{p\mu_p^2 - n\mu_n^2}{(p\mu_p + n\mu_n)}$$

Van der Pauw - Geometrie

Van der Pauw - Geometrie:



Durch Mittelung wird ein genauerer Wert erhalten:

$$\rho = \frac{\pi d}{8 \ln(2)} \left[\{R_{21,34} - R_{12,34} + R_{32,41} - R_{23,41}\} f_A + \{R_{43,12} - R_{34,12} + R_{14,23} - R_{41,23}\} f_B \right],$$

$$Q_A = \frac{R_{21,34} - R_{12,34}}{R_{32,41} - R_{23,41}}$$

$$Q_B = \frac{R_{43,12} - R_{34,12}}{R_{14,23} - R_{41,23}}$$

Widerstandsbestimmung:

$$R_{ij,kl} \equiv \frac{V_{kl}}{I_{ij}},$$

für $B = 0$:

$$\rho = \frac{\pi d}{\ln 2} \left[\frac{R_{21,34} + R_{32,41}}{2} \right] f,$$

Hallspannung erhält man:

$$V_{H42} = \frac{\rho \mu_n B_z I}{d},$$

Damit ergibt sich der Hallkoeffizient R_H :

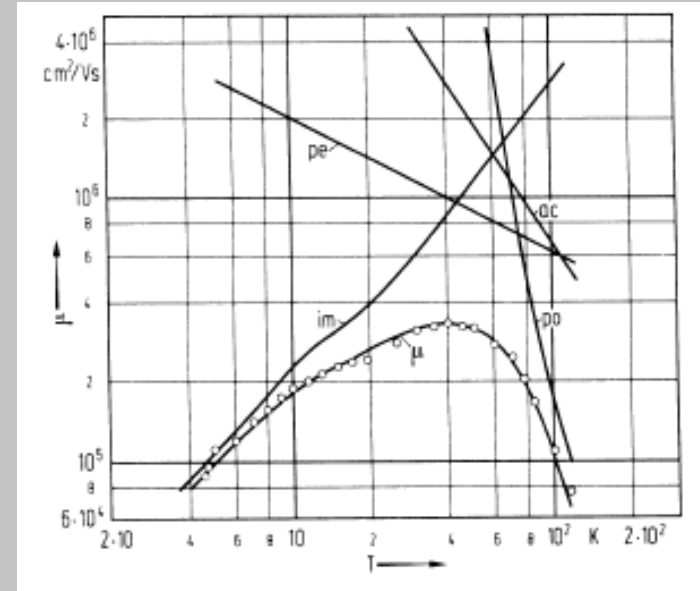
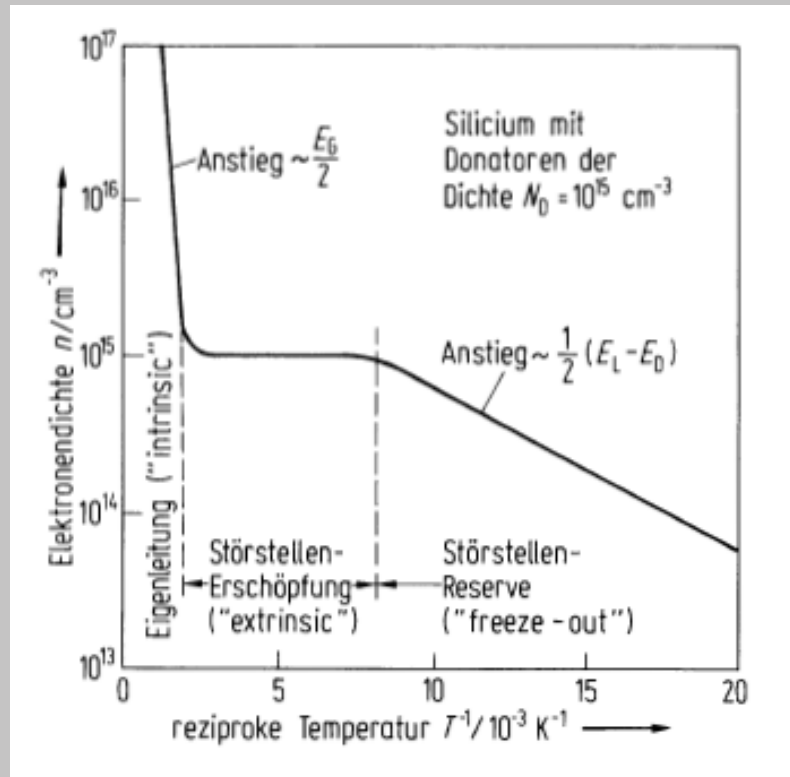
Mit d der Dicke und f ein Korrekturfaktor

$$\frac{Q-1}{Q+1} = \frac{f}{\ln 2} \operatorname{arccos} h \left\{ \frac{1}{2} \exp \left(\frac{\ln 2}{f} \right) \right\},$$

$$R_H = \frac{d}{B_z} \left[\frac{R_{31,42} + R_{42,13}}{2} \right].$$

$$Q = R_{21,34} / R_{32,41}$$

Temperaturabhängige Hall-Effekt



Streuraten: $\frac{1}{\tau_m} = \sum_i \frac{1}{\tau_m^{(i)}}$

Mathiessen-Regel: $\frac{1}{\mu} \approx \sum_i \frac{1}{\mu^{(i)}}$

nur bedingt richtig, da Mittelungsprozess $\left\langle \frac{1}{\tau_m^{(i)}} \right\rangle \neq \frac{1}{\langle \tau_m^{(i)} \rangle}$

Der Streuprozess mit der höchsten Streuraten dominiert die Beweglichkeit.

- (a) T niedrig: Störstellenstreuung
- (b) T hoch: Polar optische Streuung

Abb. 6.11 Temperaturabhängigkeit der Elektronenkonzentration einer dotierten Siliciumprobe ($N_D = 10^{15} \text{ cm}^{-3}$).

Quantumtransport in niedrigdimensionalen HL

Ermöglicht die Untersuchung außergewöhnlicher Eigenschaften wie:

- a) Quantum Hall Effekt (QHE)
- b) Shubnikov-de Haas (SdH) Effekt
- c) Ballistischen Transport
- d) fraktionalen QHE

Die Untersuchung eines 2-dim Systems in einem senkrecht dazu stehenden Magnetfeld ermöglicht die Quantisierung des Hall-Widerstands, der aus der Quantisierung der Energie in eine Reihe von Landau Niveaus. Die Landau **magnetische Länge** l_H (auch bekannt als der Zyklotronradius des untersten Landau Energieniveaus) übernimmt die Rolle einer Wellenlänge im QHE und ist gegeben durch.

$$l_H = \sqrt{\frac{\hbar}{eB}}$$

Für $B = 10 \text{ T}$ ist die magnetische Länge $l_H \sim 8.12 \text{ nm}$

Großer gyromagnetischer **g^* Faktor** aufgrund der Spinaufspaltung

$$g^* = 2 \left[1 - \left\{ \frac{1-x}{2+x} \right\} \left\{ \frac{1-y}{y} \right\} \right],$$

$$x = 1/(1 + \Delta/E_g)$$

$$y = m^*/m_0,$$

InAs $g^* = -7,6$

GaAs $g^* = -0.2$