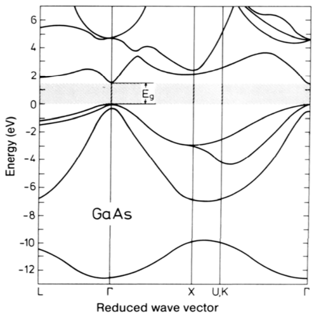
# 7. Semiconductor

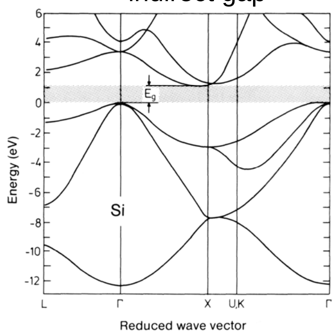


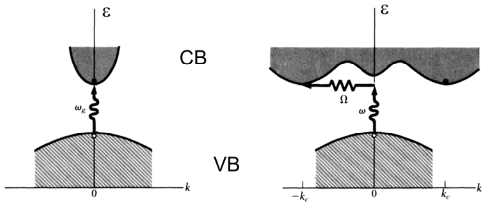
## 7.1. Bandstructure

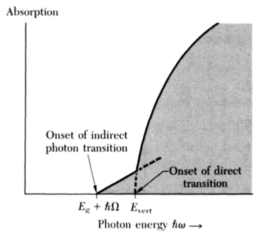
direct gap




indirect gap



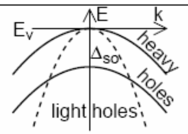




# 7.2. Semiconductor bandstructure

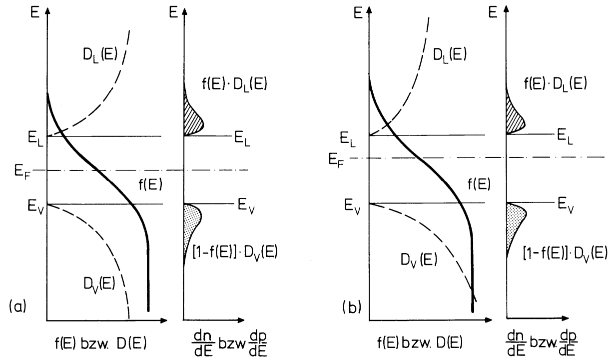


| Eigenschaft | | Si | Ge | GaAs | Einheit | |
|---|---|---|---|---|---|---|
| Gitterparameter | $a$ | 5.431 | 5.646 | 5.653 | Å | Si, Ge: Diamantstruktur |
| Atomdichte | $n_A$ | 4.99 | 4.44 | 4.43 | $10^{22}$ cm$^{-3}$ | GaAs: Zinkblende |
| Bandlücke 0 K | $E_g$ | 1.17 | 0.75 | 1.52 | eV | |
| Bandlücke 300 K | $E_g$ | 1.12 | 0.67 | 1.42 | eV | |
| Ladungsträger 300 K | $n, p$ | $10^{10}$ | $10^{13}$ | $10^{6}$ | cm$^{-3}$ | intrinsische Konzentration |
| Valenzbandmaximum | $\underline{k}$ | (000) | (000) | (000) | Γ-Punkt | |
| Masse leichter Löcher | $m^*_{lh}$ | 0.16 | 0.044 | 0.082 | $m$ | |
| Masse schwerer Löcher | $m^*_{hh}$ | 0.49 | 0.28 | 0.45 | $m$ | |
| Spin-Bahn-Aufspaltung | $\Delta_{so}$ | 0.044 | 0.29 | 0.34 | eV | |
| Valenzbandmasse | $m^*_v$ | 0.55 | 0.29 | 0.47 | $m$ | $m_v^{*3/2} = m_{lh}^{*\,3/2} + m_{hh}^{*\,3/2}$ |
| Leitungsbandminimum | $\underline{k}$ | $(\frac{4}{5}00)$ | $(\frac{1}{2}\frac{1}{2}\frac{1}{2})$ | (000) | $\frac{2\pi}{a}$ | Si: 0.8ΓX, Ge: L, GaAs: Γ |
| Anzahl der Minima | $M_c$ | 6 | 8 | 1 | | |
| Longitudinale Masse | $m^*_l$ | 0.98 | 1.57 | 0.067 | $m$ | Bewegung parallel zu $\underline{k}$ |
| Transversale Masse | $m^*_t$ | 0.19 | 0.082 | 0.067 | $m$ | Bewegung senkrecht zu $\underline{k}$ |
| Leitungsbandmasse | $m^*_c$ | 1.08 | 0.88 | 0.067 | $m$ | $m_c^{*3/2} = M_c(m_l^* m_t^* m_t^*)^{1/2}$ |




# 7.2. Intrinsic semiconductor



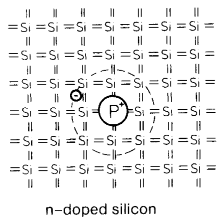


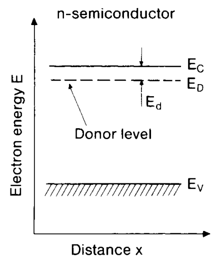

| | $E_g$ [eV] | $n_i$ [cm$^{-3}$] |
|---|---|---|
| Ge | 0,67 | $2{,}4 \times 10^{13}$ |
| Si | 1,1 | $1{,}5 \times 10^{10}$ |
| GaAs | 1,43 | $5 \times 10^{7}$ |

# 7.3. Doping of semiconductors



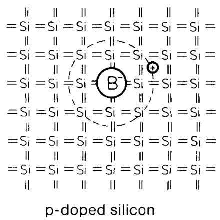
## Donor

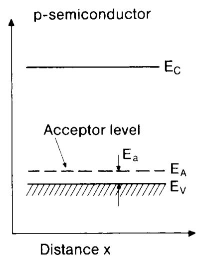



| | P | As | Sb |
|---|---|---|---|
| | [meV] | | |
| Si | 45 | 49 | 39 |
| Ge | 12 | 12,7 | 9,6 |

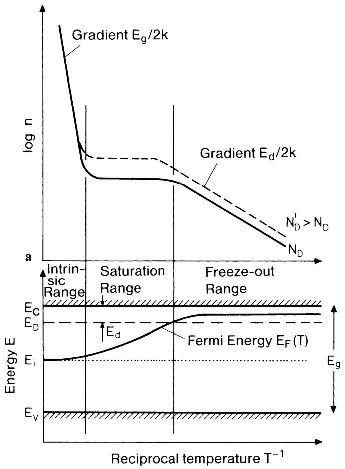
## Acceptor

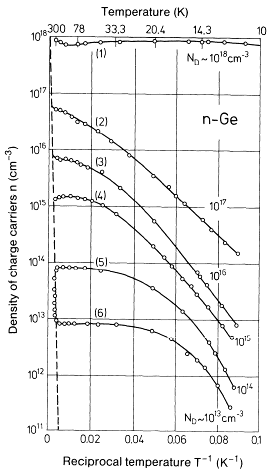



| | B | Al | Ga | In |
|---|---|---|---|---|
| | [meV] | | | |
| Si | 45 | 57 | 65 | 16 |
| Ge | 10,4 | 10,2 | 10,8 | 11,2 |

## 7.3. Carrier density




| Temperatur | Therm. Energie | Chem. Pot. $\mu$ | Bezeichnung | Ladungsträgerkonzentration | |
|---|---|---|---|---|---|
| niedrig | $k_BT < E_d$ | $> E_D$ | Reserve | $n \propto e^{-E_d/2k_BT}$ | Wichtig für Halbleiter-bauelemente! |
| mittel | $E_d < k_BT < E_g$ | $< E_D$ | Erschöpfung | $n = n_D =$ const. | |
| hoch | $E_g < k_BT$ | $\approx \frac{1}{2}(E_v + E_c)$ | Intrinsisch | $n \propto e^{-E_g/2k_BT}$ | |



## 7.4. pn-junction

diffusion (recombination) current:
e in n → p, h in p → n

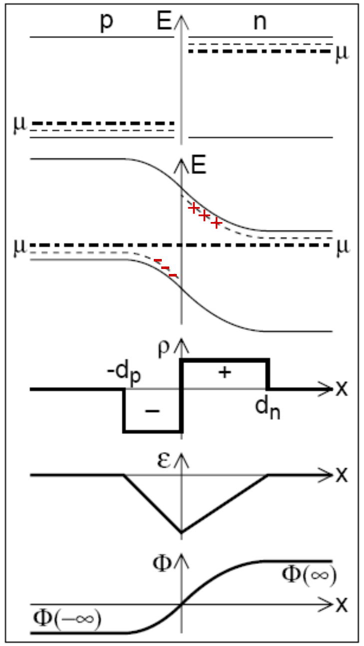
field (generation) current:
e generated in p → n
h generated in n → p

in equilibrium: $I_{gen} = I_{rec}$ , $\mu$ = const.

space charge layer:
fixed positively charged donors (in n)
and negatively charged acceptors (in p)

Electric field and potential
according to Poisson equation:

$$\nabla^2\Phi = -\frac{\rho}{\epsilon\epsilon_0}, \;\; \vec{\mathcal{E}} = -\nabla\Phi$$






## 7.4. pn-junction

$$e(\Phi(\infty)-\Phi(-\infty)) = e\Delta\Phi = E_c - E_v + k_BT \ln \frac{n_A n_D}{N_C^{eff} N_V^{eff}}$$

Schottky´s approximation (square charge distributions)

$$\Delta\Phi = \frac{e}{2\epsilon\epsilon_0}(n_A d_p^2 + n_D d_n^2)$$

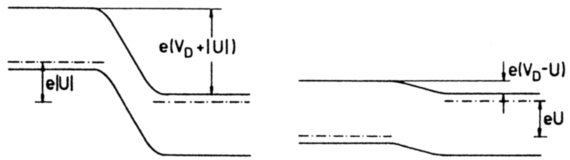
Space charge region $\quad d_p \cdot n_A = d_n \cdot n_D$

$$d_n = \sqrt{\frac{2\epsilon\epsilon_0}{e}\frac{n_A/n_D}{n_A+n_D}\Delta\Phi} \qquad d_p = \sqrt{\frac{2\epsilon\epsilon_0}{e}\frac{n_D/n_A}{n_A+n_D}\Delta\Phi}$$

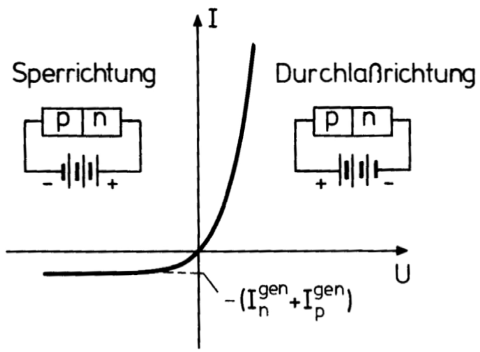
$$\mathcal{E} \approx 10^6 \text{ V/m} \qquad d \approx 10^2 - 10^4 \text{ Å}$$



## 7.4. pn-junction

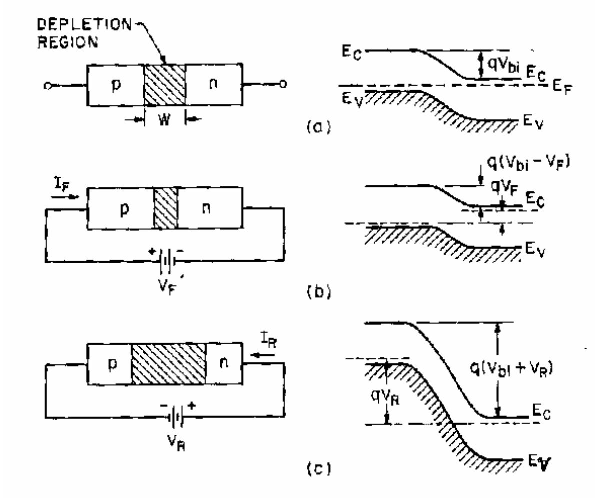



$$I = I_{gen}(e^{eU/k_BT} - 1)$$



# 7.4. pn-junction






open circuit

forward bias

reversed bias

# 7.4. pn-junction



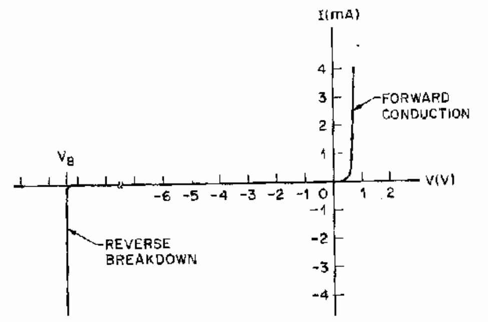
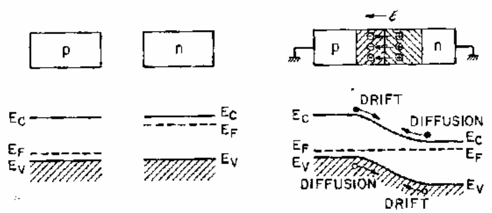
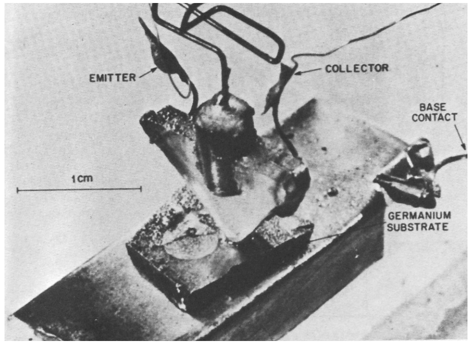



**Fig. 1** Current-voltage characteristics of a typical silicon *p–n* junction.

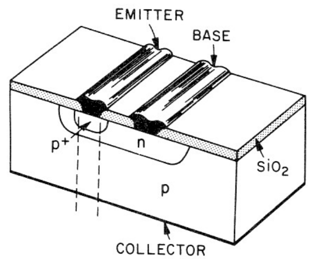



# 7.5. Bipolar transitor






First transistor - Bell labs 1947




p-n-p transistor – planar technology

# 7.5. Transitors



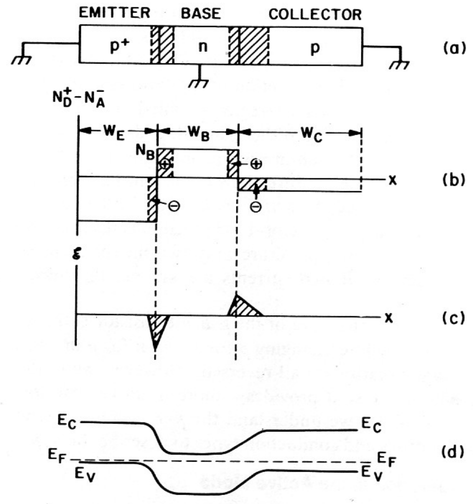



**Fig. 3** (*a*) A *p-n-p* transistor with all leads grounded. (*b*) Doping profile of a transistor with abrupt impurity distributions. The crosshatched areas are the depletion regions. (*c*) Electric-field profile. (*d*) Energy band diagram at thermal equilibrium.

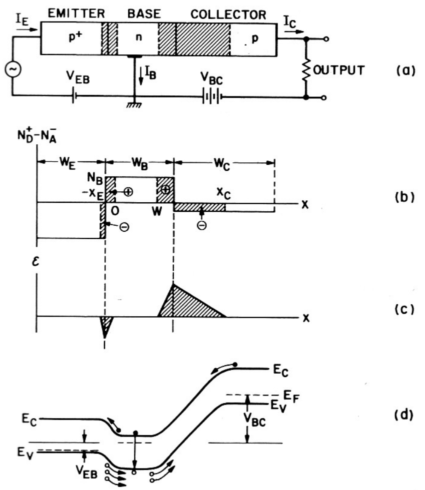


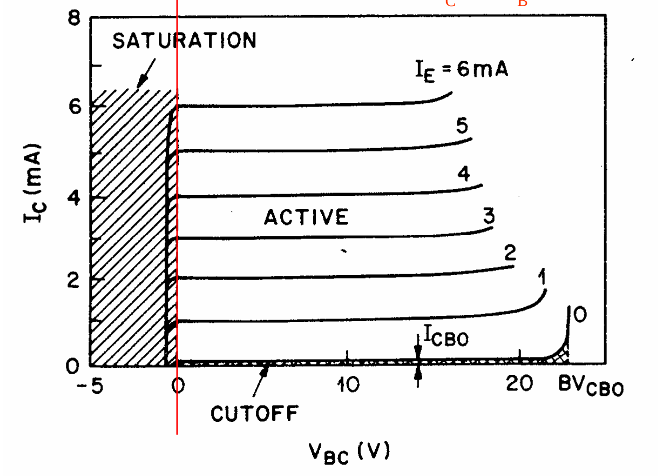

**Fig. 4** (*a*) The transistor shown in Fig. 3 under the active mode of operation.[3] (*b*) Doping profiles and the depletion regions under biasing conditions. (*c*) Electric-field profile. (*d*) Energy band diagram.



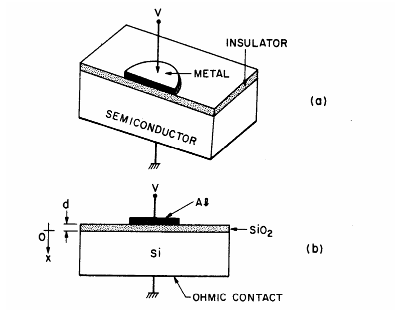
Basis-Kollektor in Durchlassrichtung

Basis-Kollektor in Sperrrichtung

Kollektorstrom ~ Emitterstrom
hohe Stromverstärkung ß
$I_C = ß \cdot I_B$






(*a*) Perspective view of an MOS diode. (*b*) Cross section of an MOS diode.

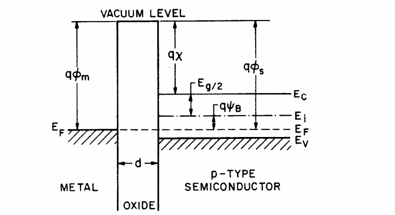
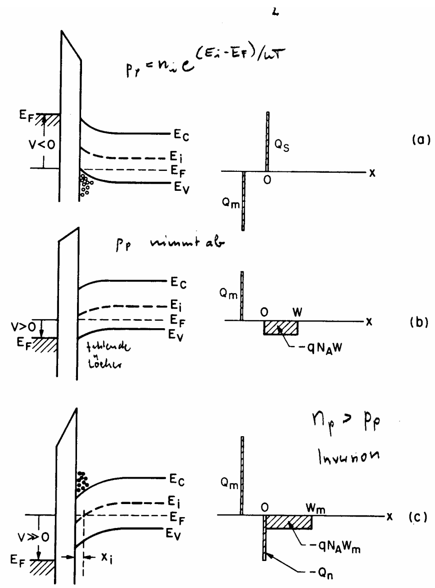



**Fig. 22** Energy band diagram of an ideal MOS diode at $V = 0$.



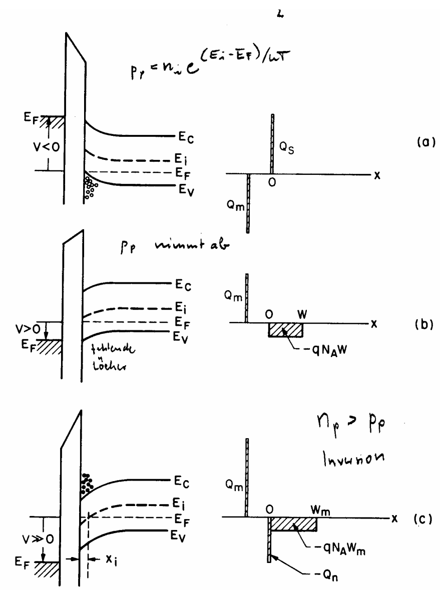



a) Accumulation

b) Depletion

c) Inversion

$$
\begin{aligned}
n &= N_L \exp -(\frac{E_L - E_F}{kT}) \\
&= N_L \exp -(\frac{E_L - E_i}{kT}) \exp(\frac{E_F - E_i}{kT}) \\
n &= n_i \cdot \exp(\frac{E_F - E_i}{kT}) \\
p &= n_i \cdot \exp(\frac{E_i - E_F}{kT})
\end{aligned}
$$



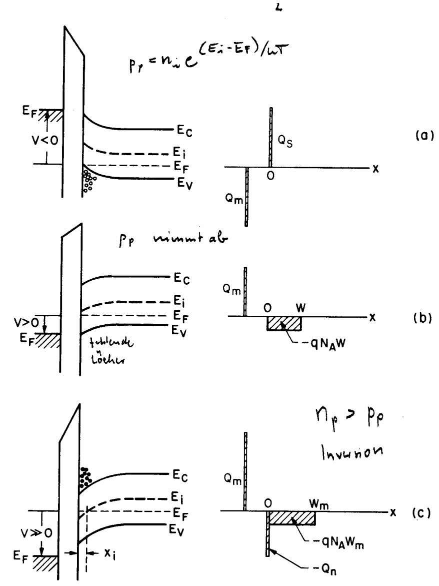
## 7.5. MOS diode

a) Accumulation

b) Depletion

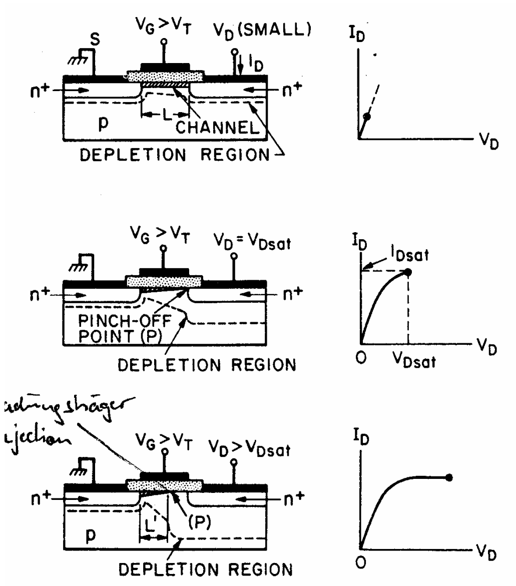
c) Inversion

$$\begin{aligned} n &= N_L \exp -(\frac{E_L - E_F}{kT}) \\ &= N_L \exp -(\frac{E_L - E_i}{kT}) \exp(\frac{E_F - E_i}{kT}) \\ n &= n_i \cdot \exp(\frac{E_F - E_i}{kT}) \\ p &= n_i \cdot \exp(\frac{E_i - E_F}{kT}) \end{aligned}$$






## 7.5. MOSFET




$V_T$: Spannung für die Inversionskanal (n) existiert
$V_G$: gate Spannung
$V_D$: drain Spannung

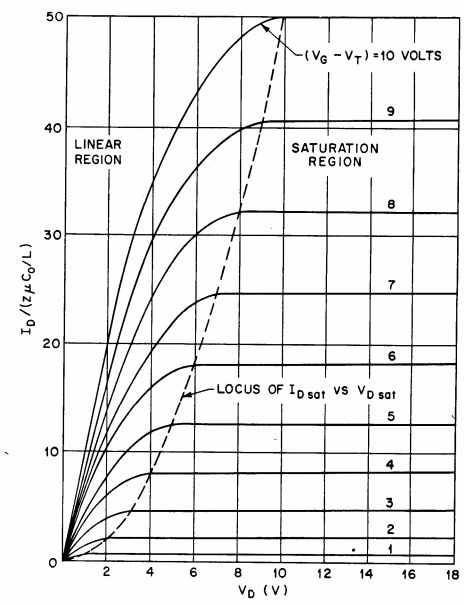
$V_D > 0$ bedeutet $n_{drain}$-p Übergang in Sperrrichtung

$V_D = V_{Dsat} >> 0$
$n_{drain}$-p Verarmungszone ausgedehnt, leitender Kanal wird eingeschnürt (= pinch-off point)

$V_D > V_{Dsat}$
$n_{drain}$-p Verarmungszone weiter ausgedehnt, leitender Kanal wird zurückgedrängt, Injektion von Elektronen aus Kanal in p-Schicht und Absaugen in $n_{drain}$ analog zu Bipolartransitor, Drainstrom $I_D$ in Sättigung



## 7.5. MOSFET

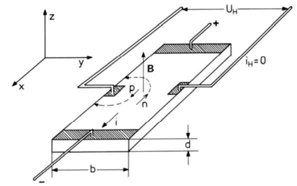


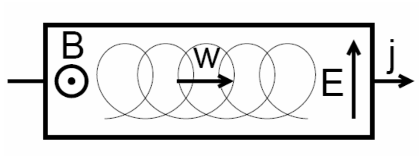



## 7.6. Hall Effect E ⊥ B

$$\hbar \dot{\vec{k}} = -e(\vec{\mathcal{E}} + \vec{v} \times \vec{B}) = -e(\vec{v} - \vec{w}) \times \vec{B}$$

Drift velocity: $\vec{w} = \frac{\vec{\mathcal{E}} \times \vec{B}}{B^2}$ $\qquad \vec{j} = -ne\ \vec{w}$



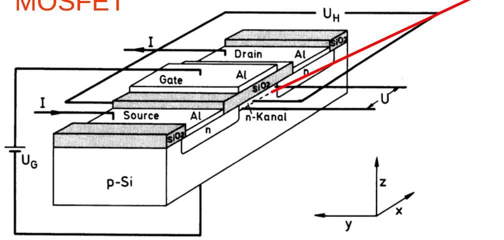

$$\boxed{\begin{aligned} &\text{Hall field: } E_y = R_H\ j_x \cdot B,\ j_y = 0 \\ &\text{Hall coefficient: } R_H = -1/ne \end{aligned}}$$

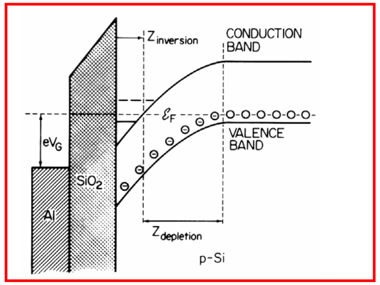
Non-closed orbits or carriers with different mobility or concentration
⇒ $R_H$ depends on magnetic field B

# 7.6. Hall Effect $E \perp B$

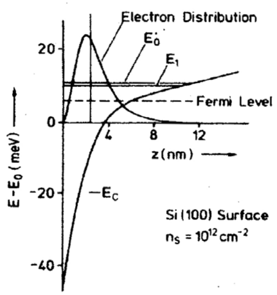


MOSFET




Inversion layer

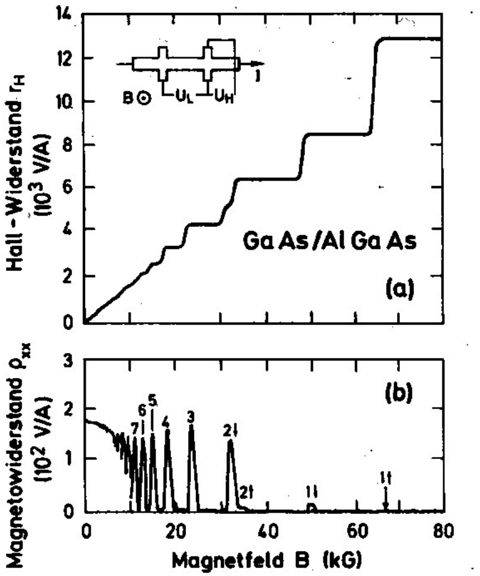



Leads to quantization into levels $E_n$

2d - electron gas

# 7.6. Quantum Hall Effect






Quantum Hall Effekt
NP 1985, Klaus v. Klitzing

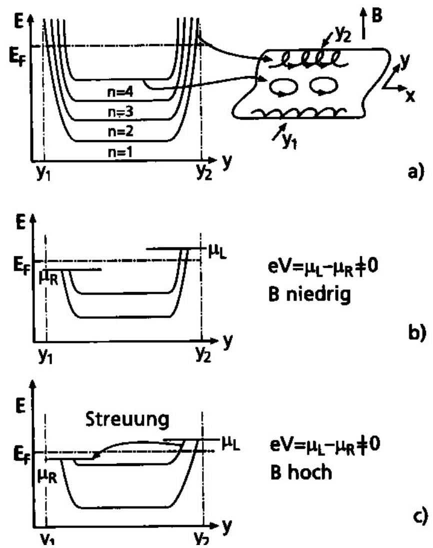
$$r_H = \frac{U_H}{I} = \frac{h}{e^2}\frac{1}{\nu},$$
$$\nu = 1, 2, \ldots$$

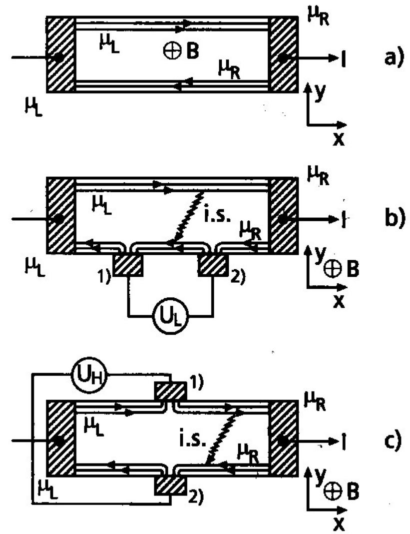
Shubnikov - de Haas
Oszillationen des Magentowiderstands

# 7.6. Quantum Hall Effect



Transport via 1d edge channels




$$I = \frac{e^2}{h} \cdot \nu \cdot V, \;\; \nu = 1, 2, \ldots$$