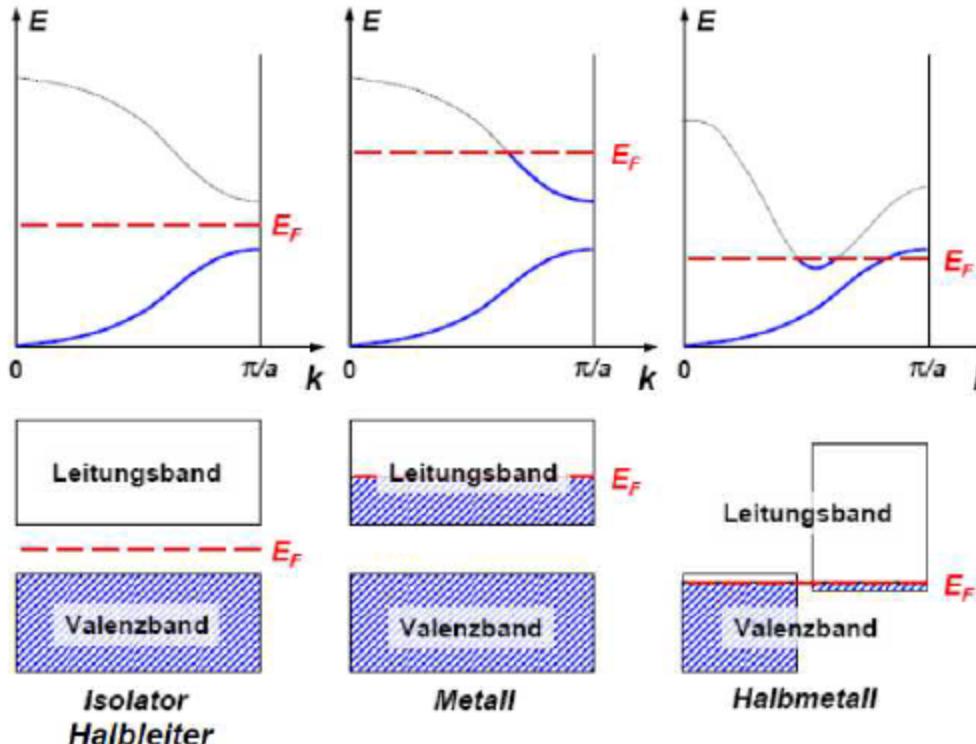
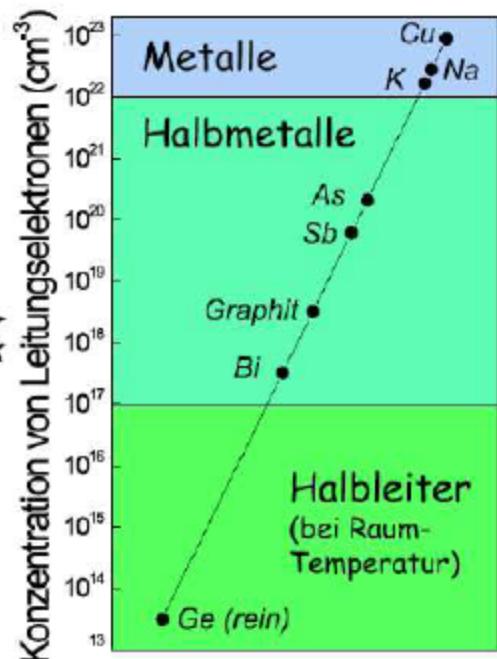


# Metalle, Halbmetalle, Halbleiter, Isolatoren

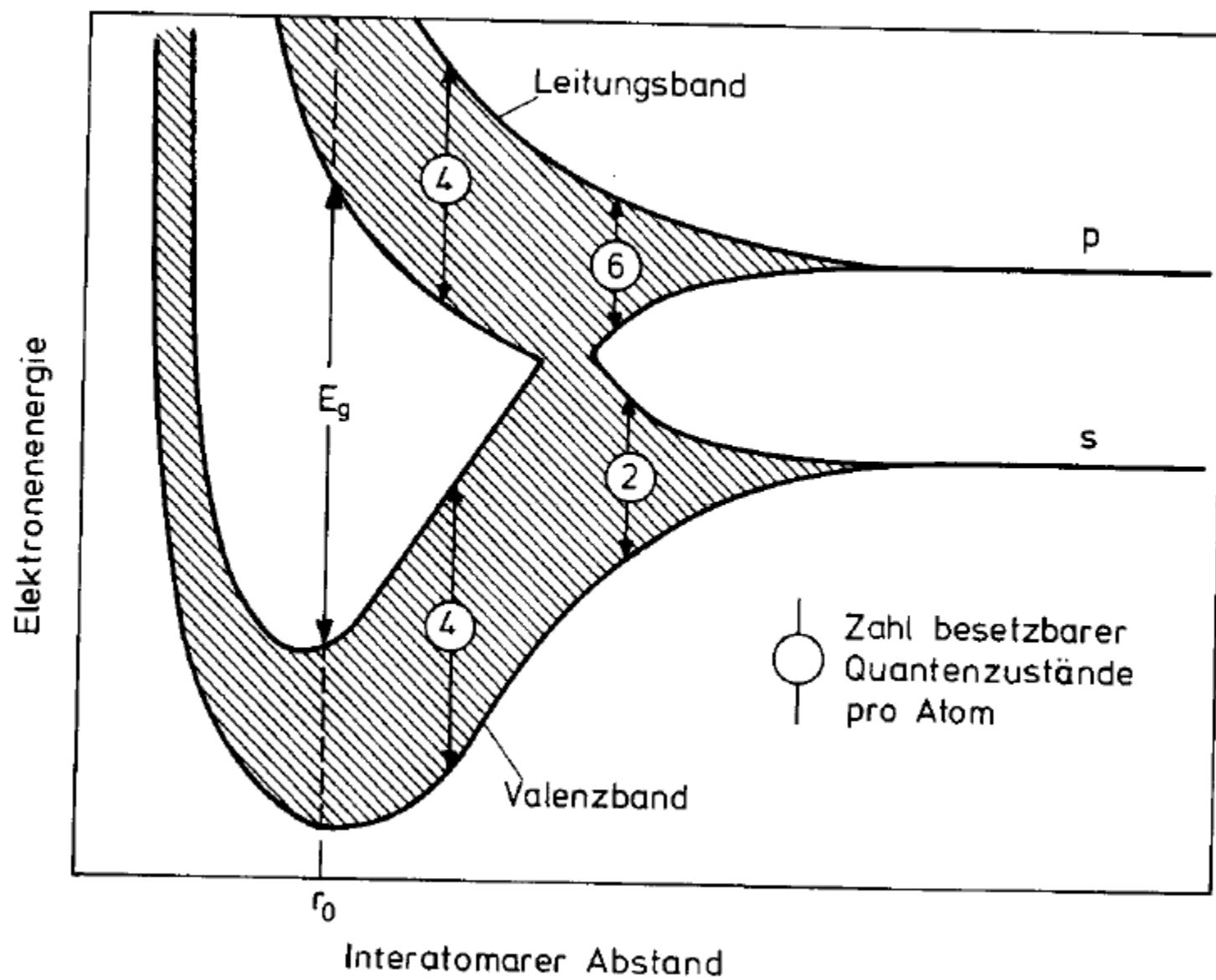


Lage des Fermi-Niveaus im Bänderschema für Isolatoren, Halbleiter, Metalle und Halbmetalle

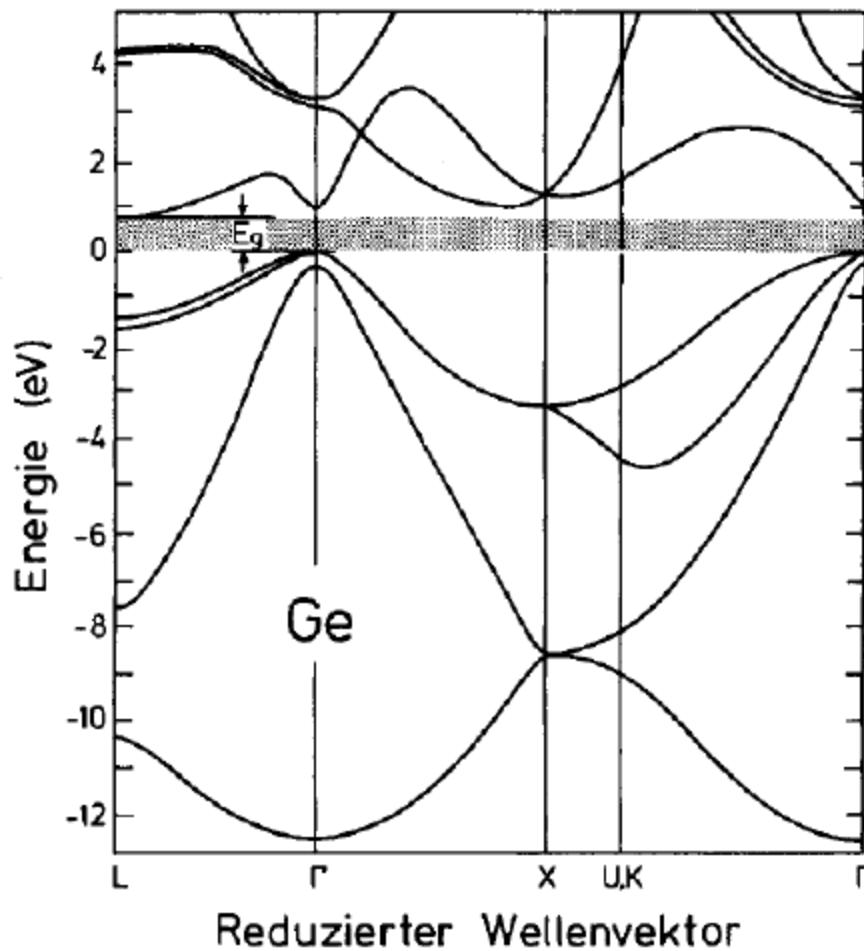


Ladungsträgerkonzentration:  
Halbleiter, Halbmetalle, Metalle

## sp<sup>3</sup> Hybridisierung



## Halbleiter mit *indirekter* Bandlücke

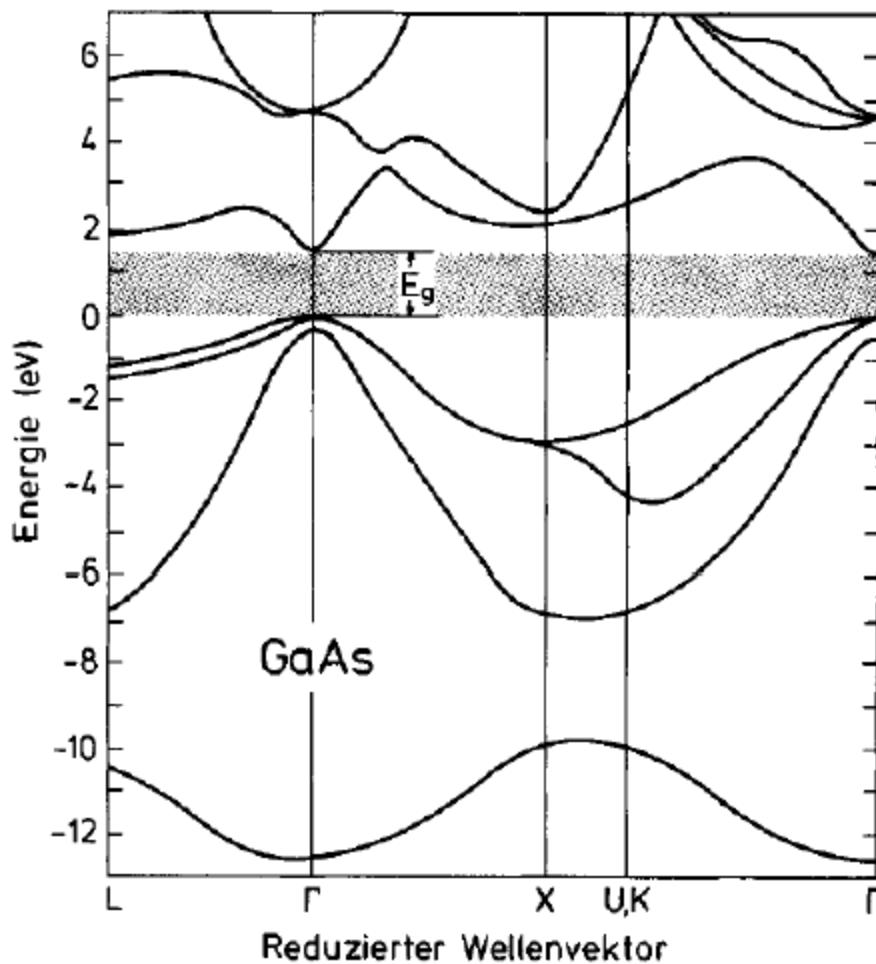


bei 300 K:

Si: 1,11 eV

Ge: 0,66 eV

## Halbleiter mit *direkter* Bandlücke



bei 300 K:

GaAs: 1,43 eV  
InSb: 0,17 eV

(wichtig bei  
Lichtemission)

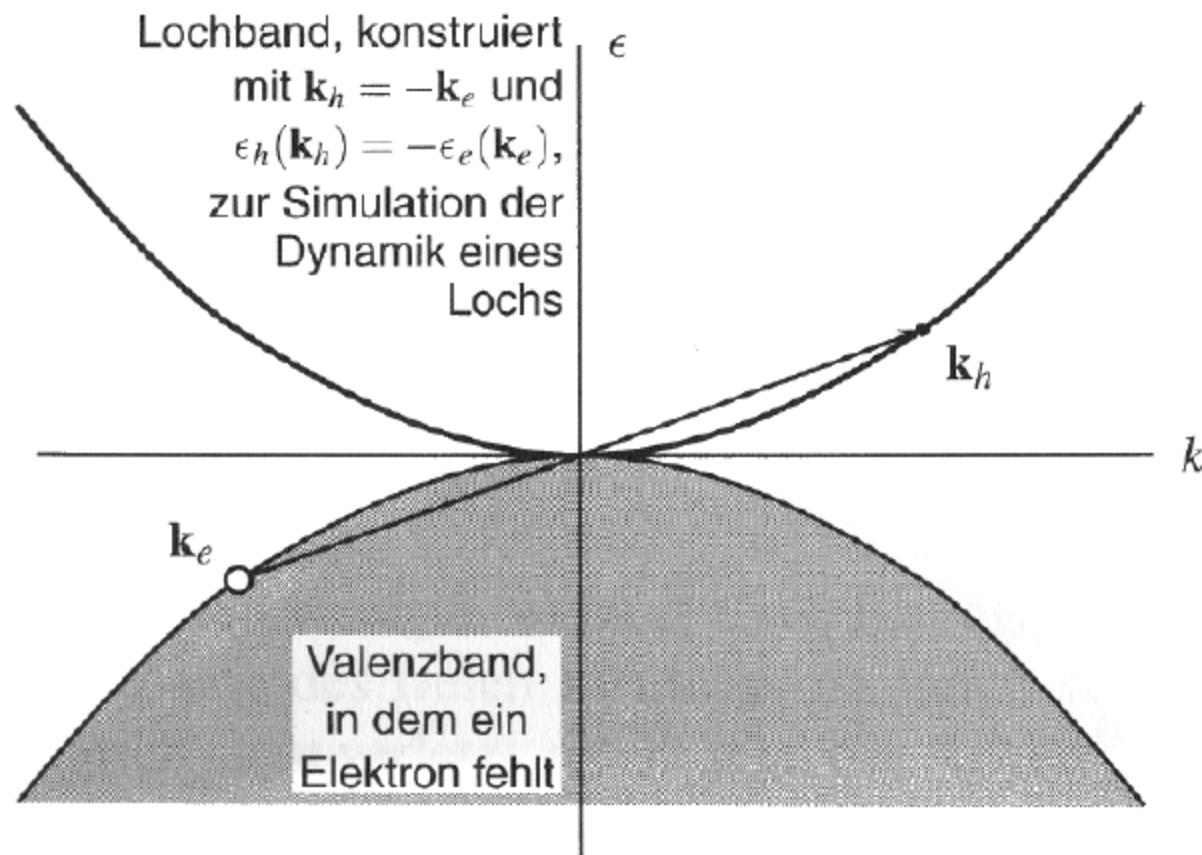
## Masse von Bandelektronen im Feld

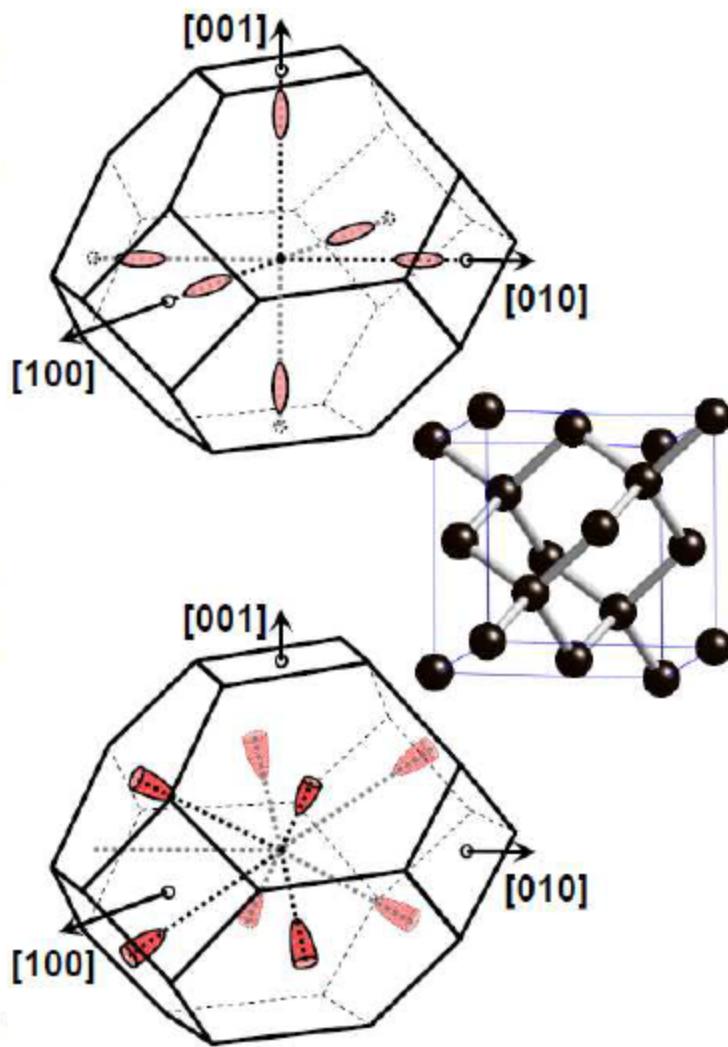
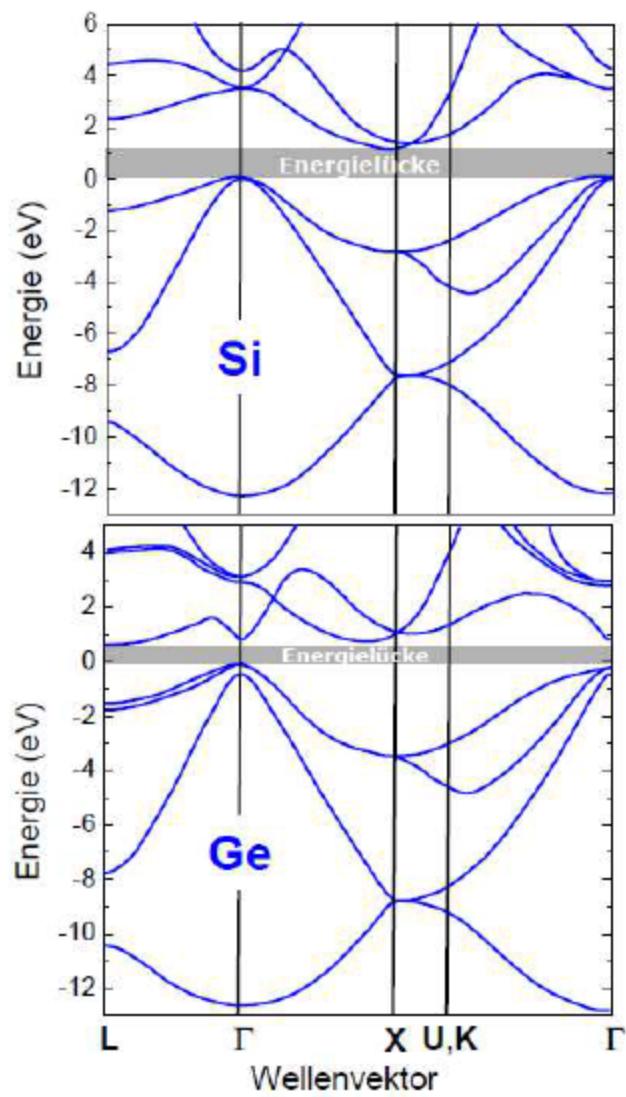
effektive Masse:  $\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{d^2 E}{dk^2}$  (Bandkrümmung)

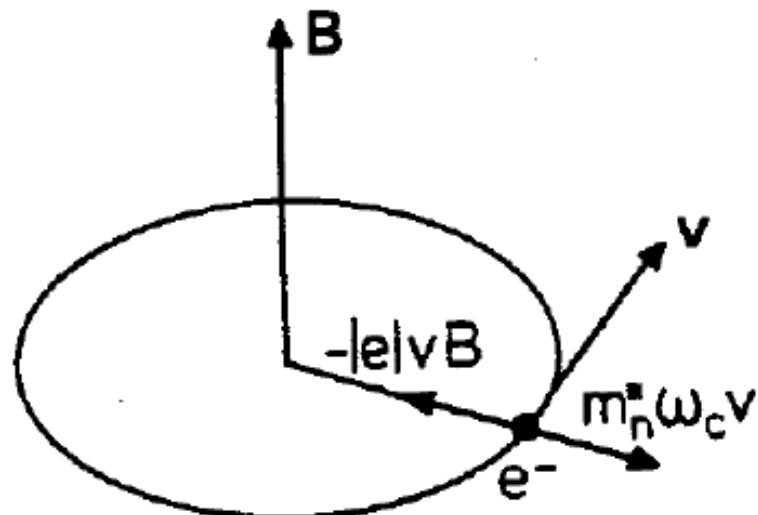
- groß nahe der Grenze der Brillouinzone (Bragg-Reflexion!)
- **negativ** an Bandoberkante

anderes Konzept: **Löcher**  
(positive Ladung statt negativer Masse)

## Elektronenbänder und Lochbänder in HL



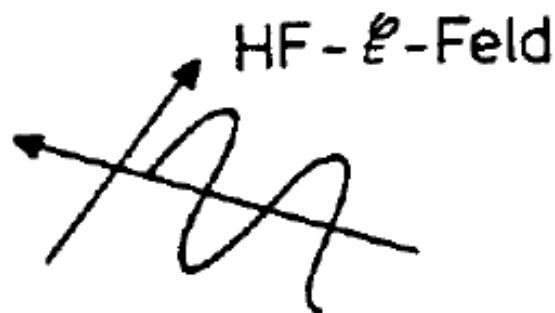




$$e \cdot v \cdot B = m_0 \cdot \omega_c \cdot v$$

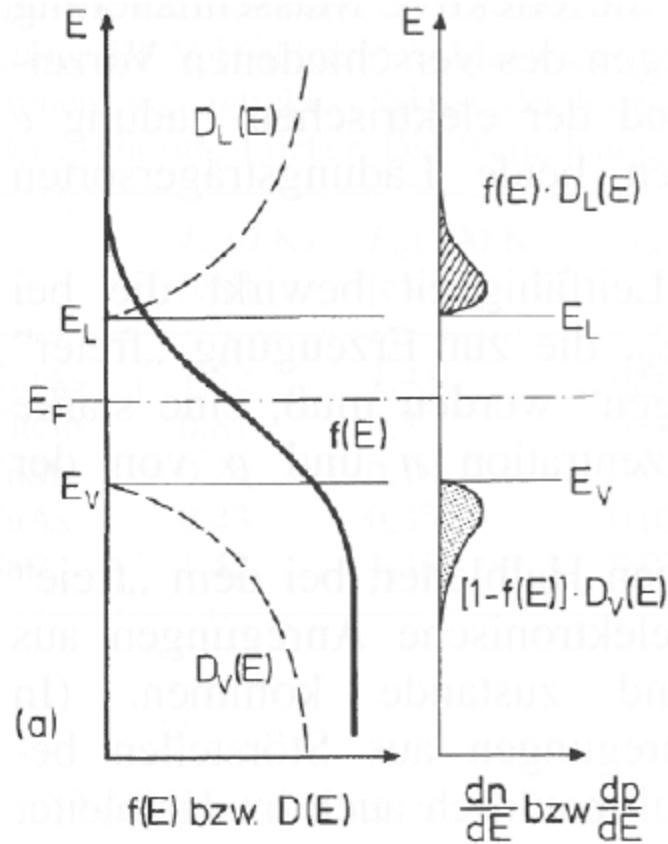
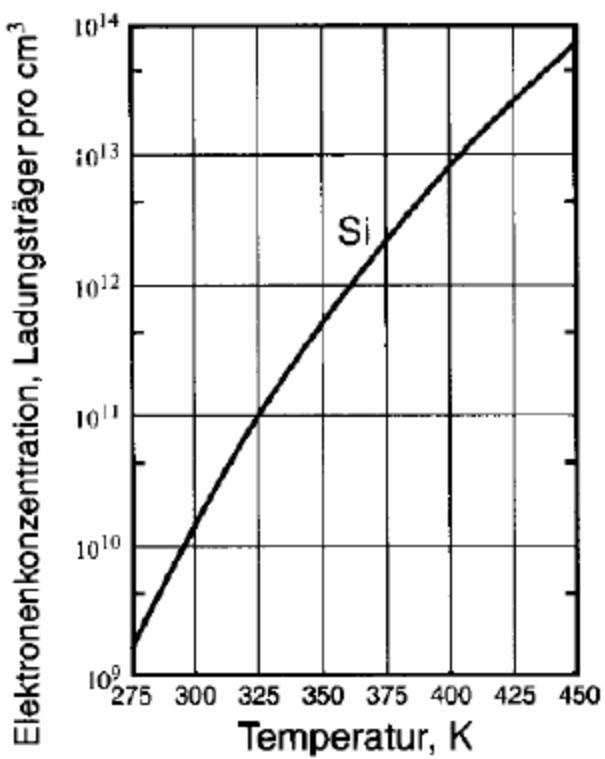
$$\omega_c = \frac{e \cdot B}{m_0}$$

$$m_c := \frac{e \cdot B}{\omega_c} = \frac{e \cdot B}{2\pi} \cdot T$$



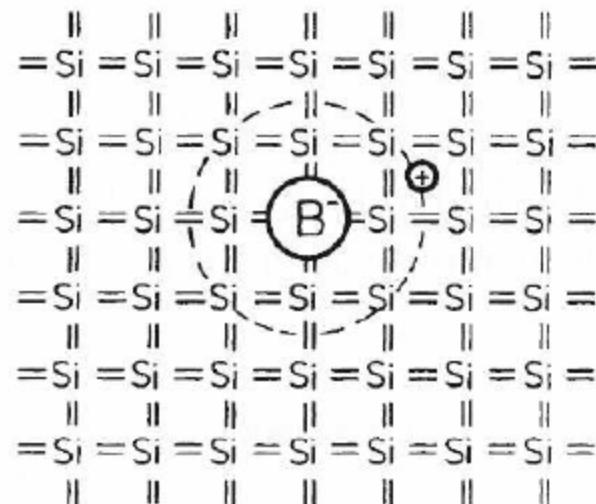
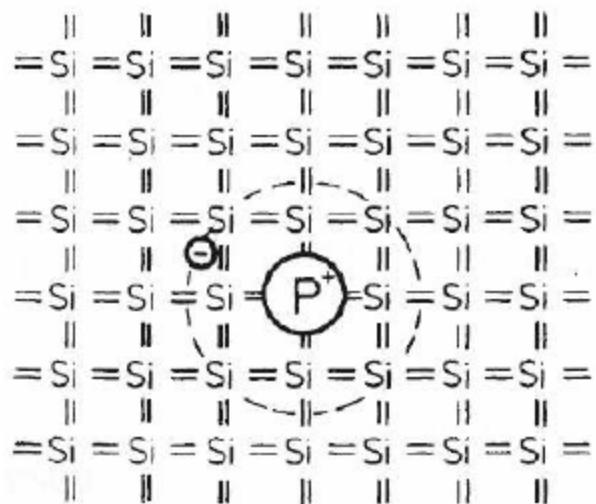
| Halbleiter | $m_e^*/m$ | $m_{el}^*/m$ | $m_{et}^*/m$ | $m_{lh}^*/m$ | $m_{hh}^*/m$ | $m_{soh}^*/m$ | $\Delta$ (eV) |
|------------|-----------|--------------|--------------|--------------|--------------|---------------|---------------|
| Si         |           | 0.19         | 0.98         | 0.15         | 0.54         | 0.23          | 0.044         |
| Ge         |           | 0.082        | 1.57         | 0.043        | 0.34         | 0.095         | 0.295         |
| GaAs       | 0.07      |              |              | 0.08         | 0.53         | 0.15          | 0.341         |
| GaSb       | 0.047     |              |              | 0.05         | 0.8          | 0.15          | 0.75          |
| GaP        |           |              |              | 0.18         | 0.57         | 0.25          | 0.08          |
| InAs       | 0.026     |              |              | 0.026        | 0.41         | 0.14          | 0.38          |
| InP        | 0.073     |              |              | 0.12         | 0.58         | 0.12          | 0.11          |
| InSb       | 0.015     |              |              | 0.016        | 0.42         | 0.12          | 0.81          |

## Ladungsträger in intrinsischen Halbleitern



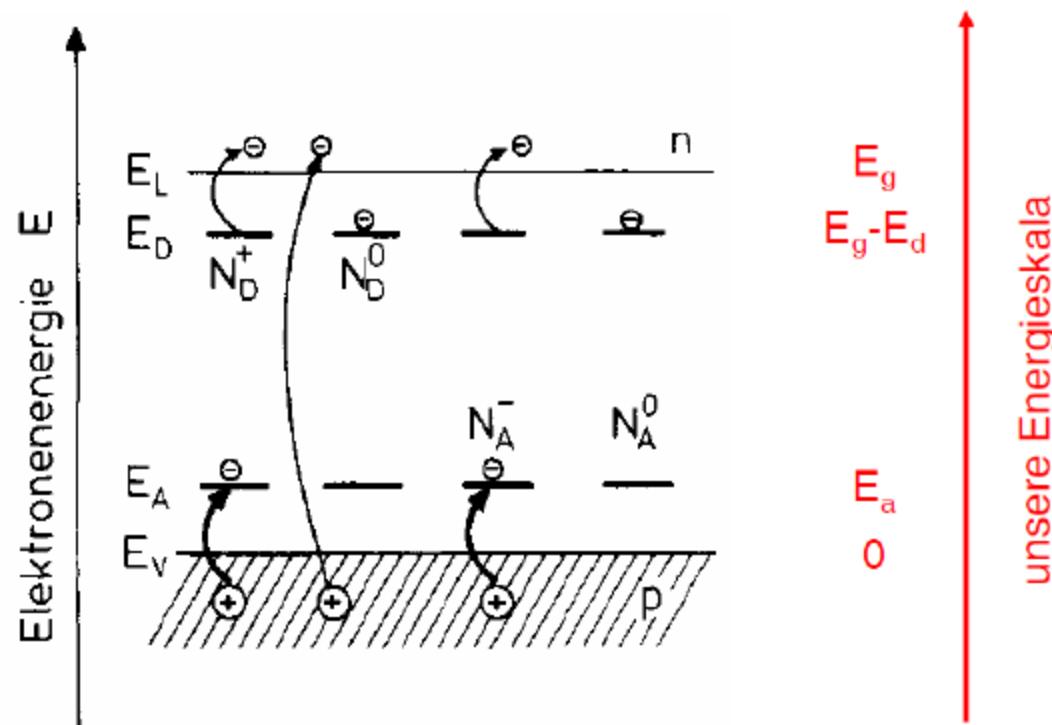
## Donatoren und Akzeptoren in Silizium

182



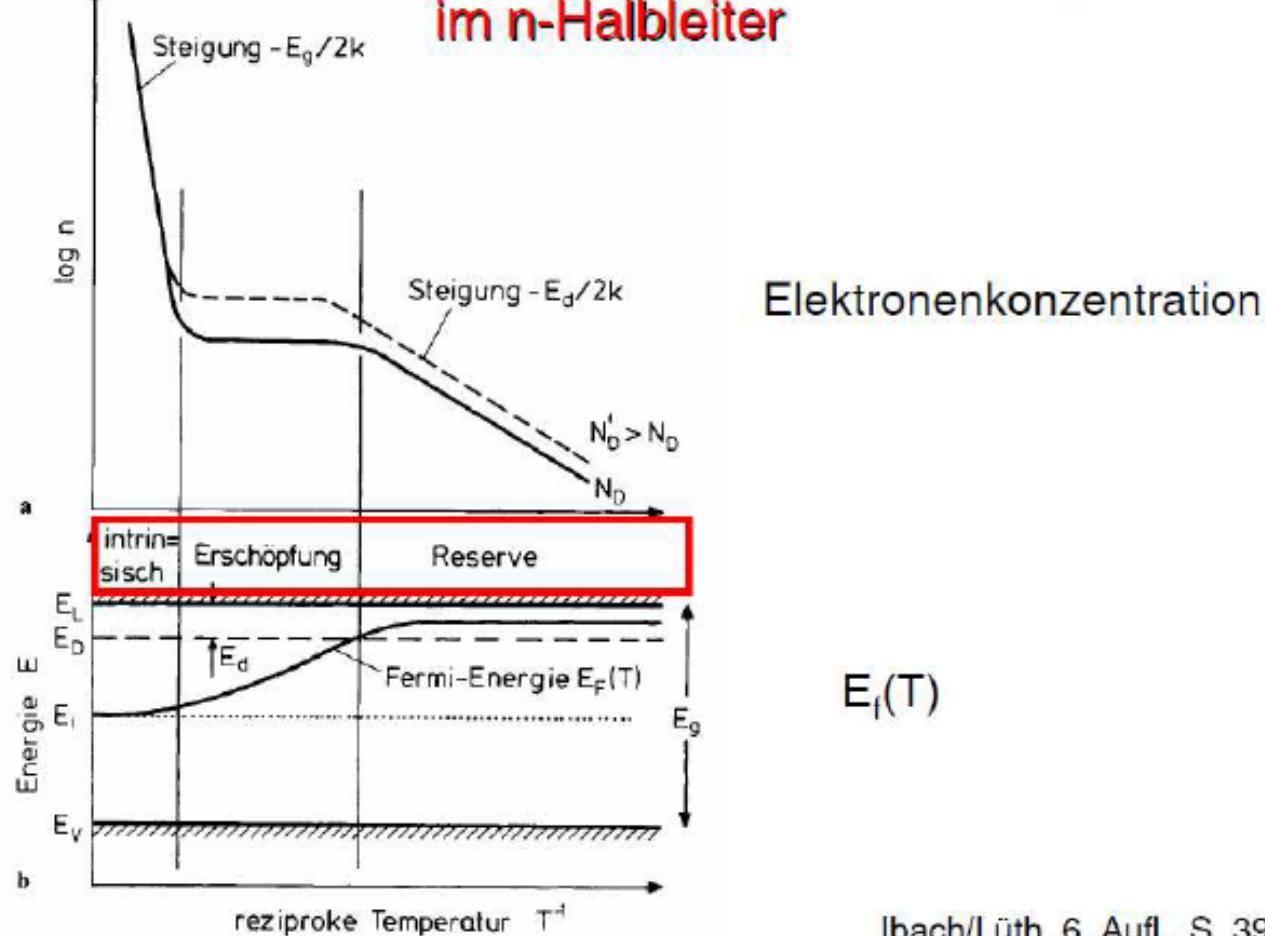
## Ladungsträger- und Störstellenkonzentrationen in dotierten Halbleitern

183



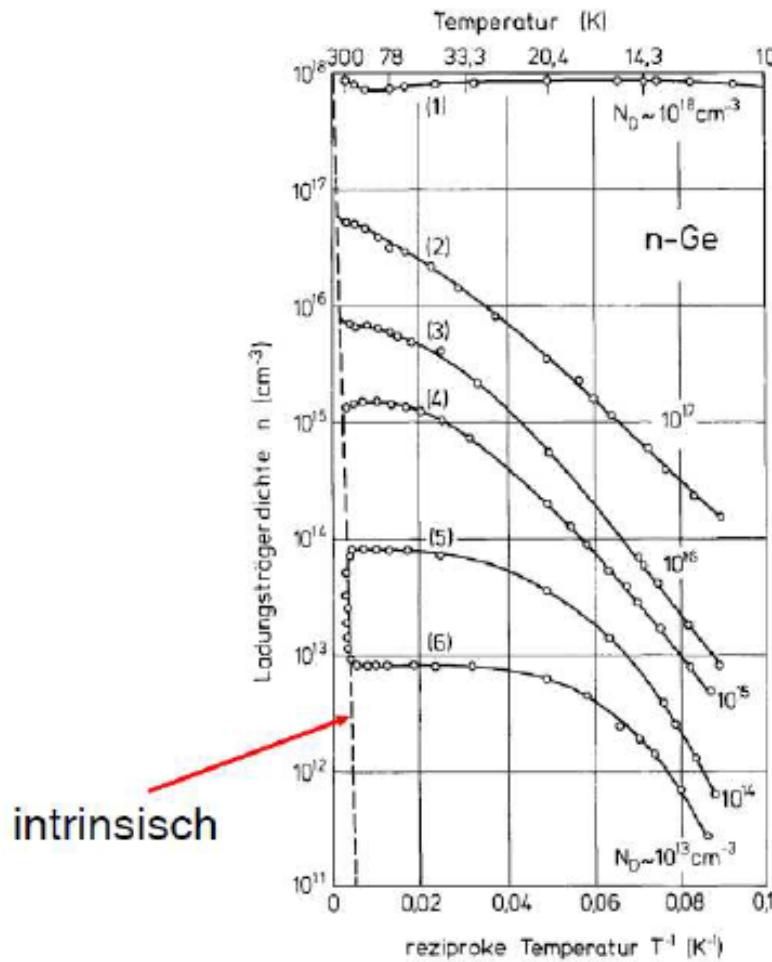
Ibach/Lüth, 6. Aufl., S. 395

## Elektronenkonzentration und Fermi-Energie im n-Halbleiter



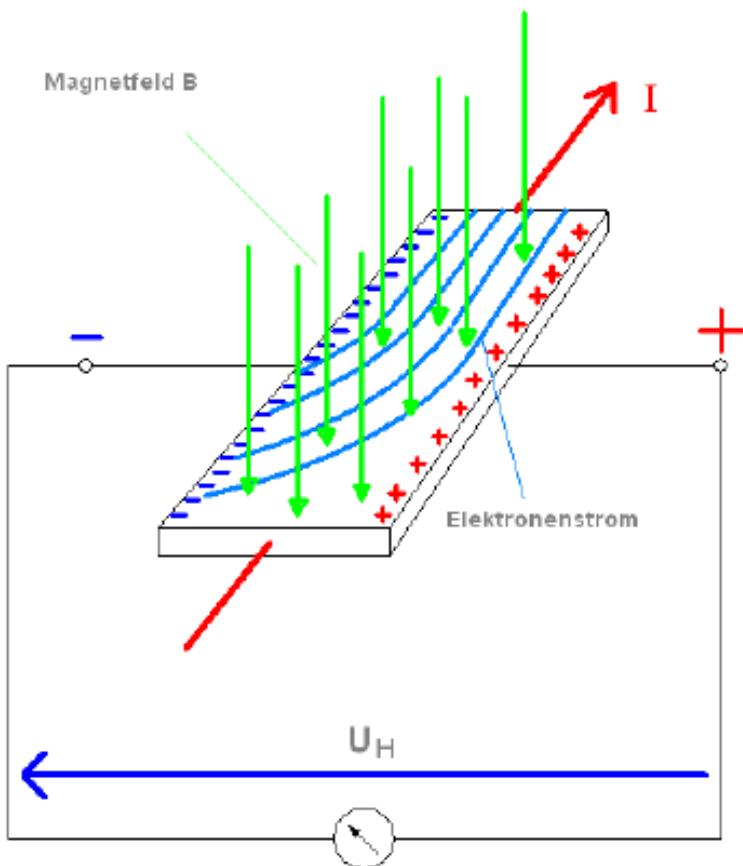
Ibach/Lüth, 6. Aufl., S. 398

## Elektronenkonzentration in n-Germanium



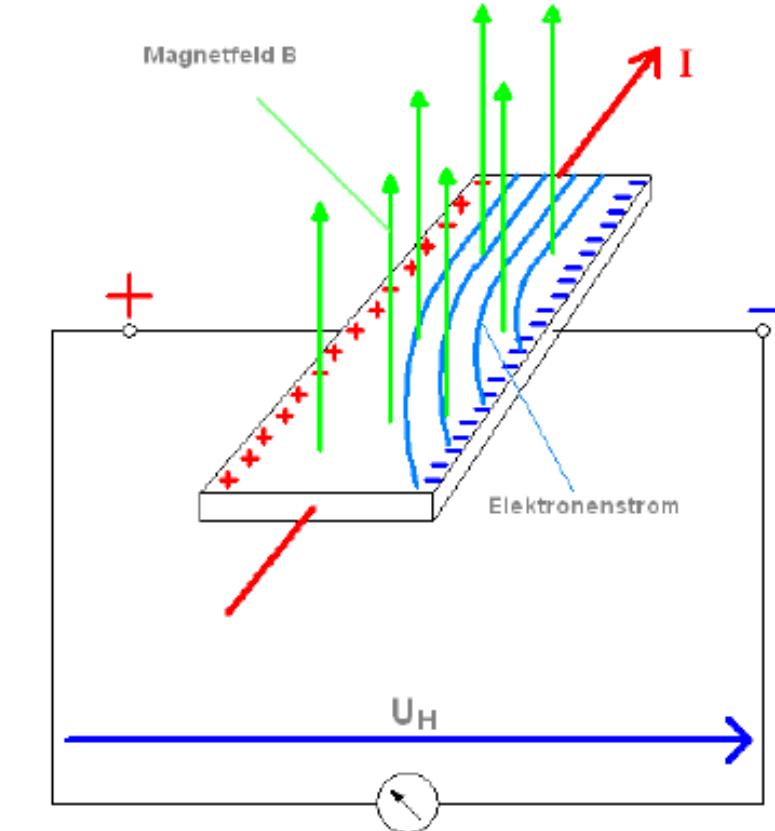
Messung durch  
Hall-Effekt

## Hall-Effekt



$$U_H = \frac{R_H \cdot B \cdot I}{d}$$

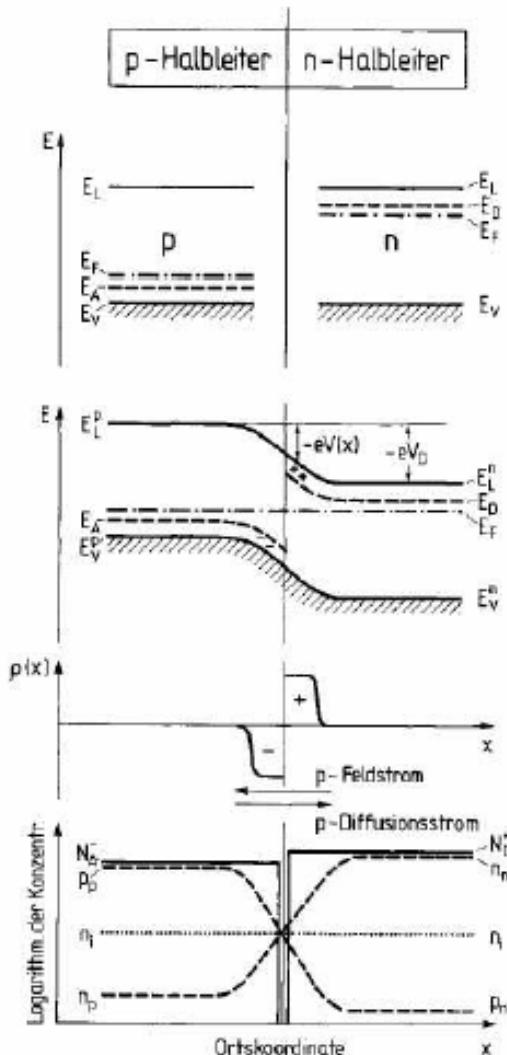
$$R_H = 1/-(n \cdot e)$$



Bei Halbleitern :

$$R_H = [p\mu_p^2 + n\mu_n^2] / [e(p\mu_p + n\mu_n)^2]$$

## p-n-Übergang im thermischen Gleichgewicht



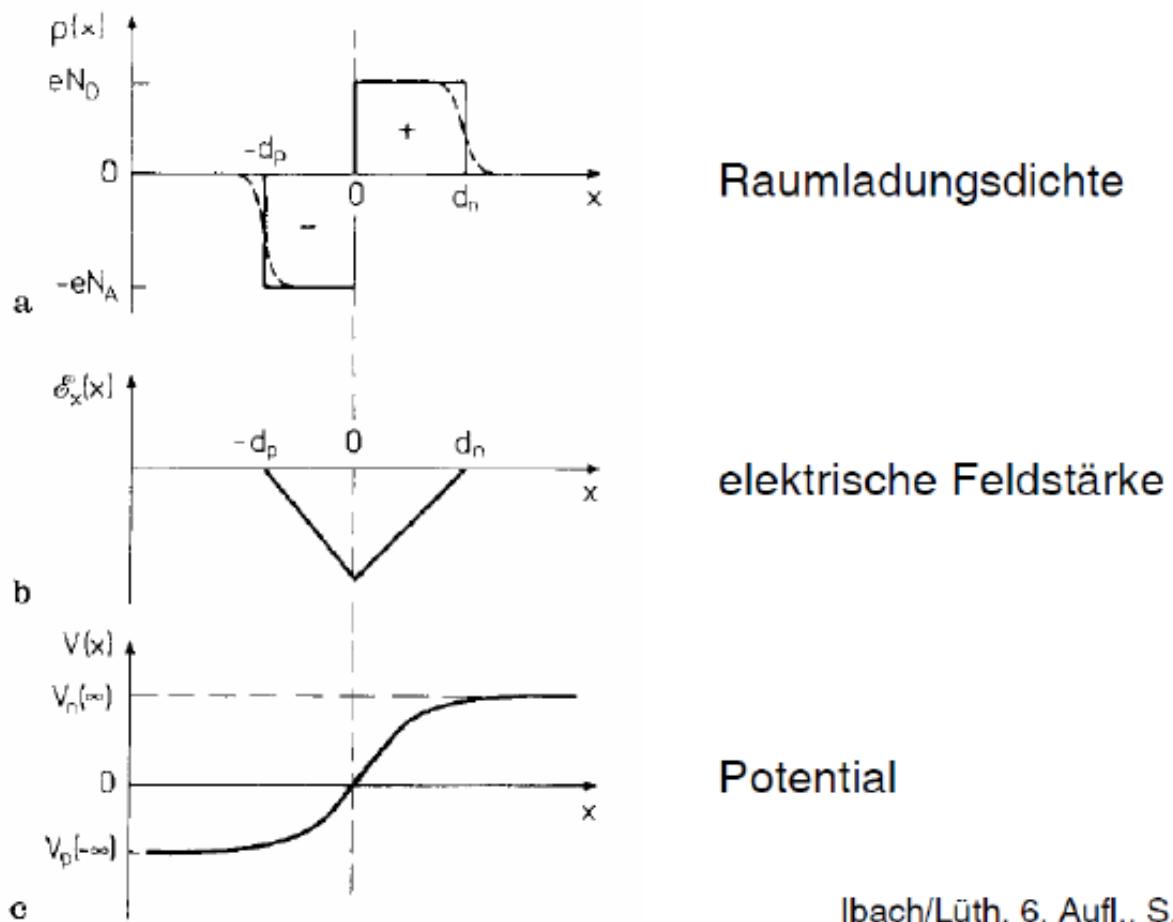
p-n getrennt

p-n zusammengefügten  
(Bandverbiegung)

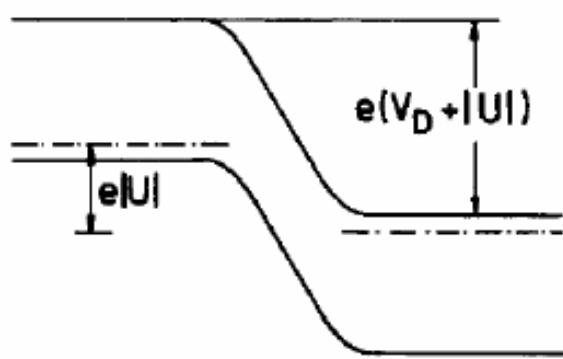
Raumladung

Ladungsträgerkonzentrationen

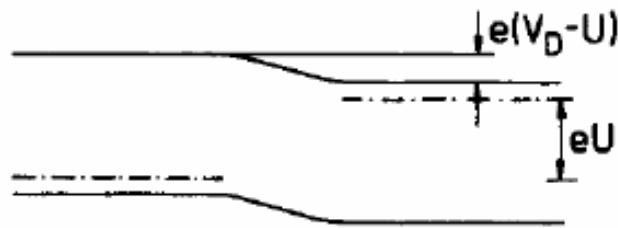
## Schottky-Modell der Raumladungszone



## Bänderschema eines p-n-Übergangs mit Spannung <sup>188</sup>



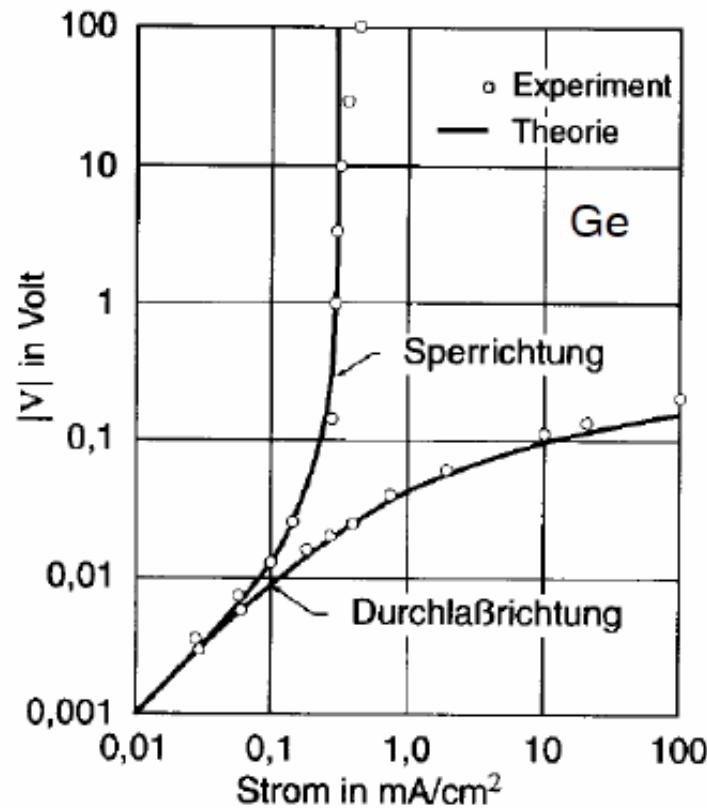
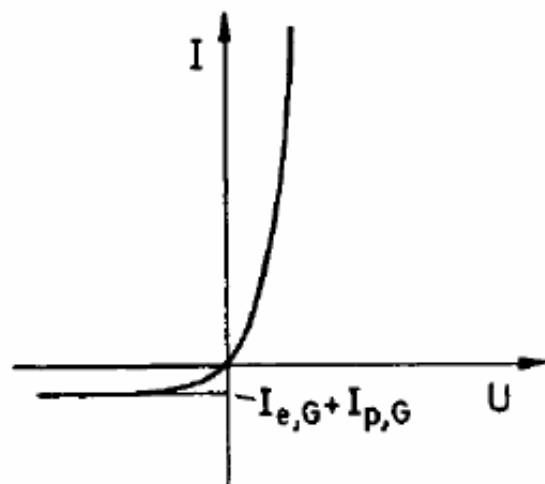
Sperrrichtung



Durchlaßrichtung

## Strom-Spannungs-Kennlinie eines p-n-Übergangs

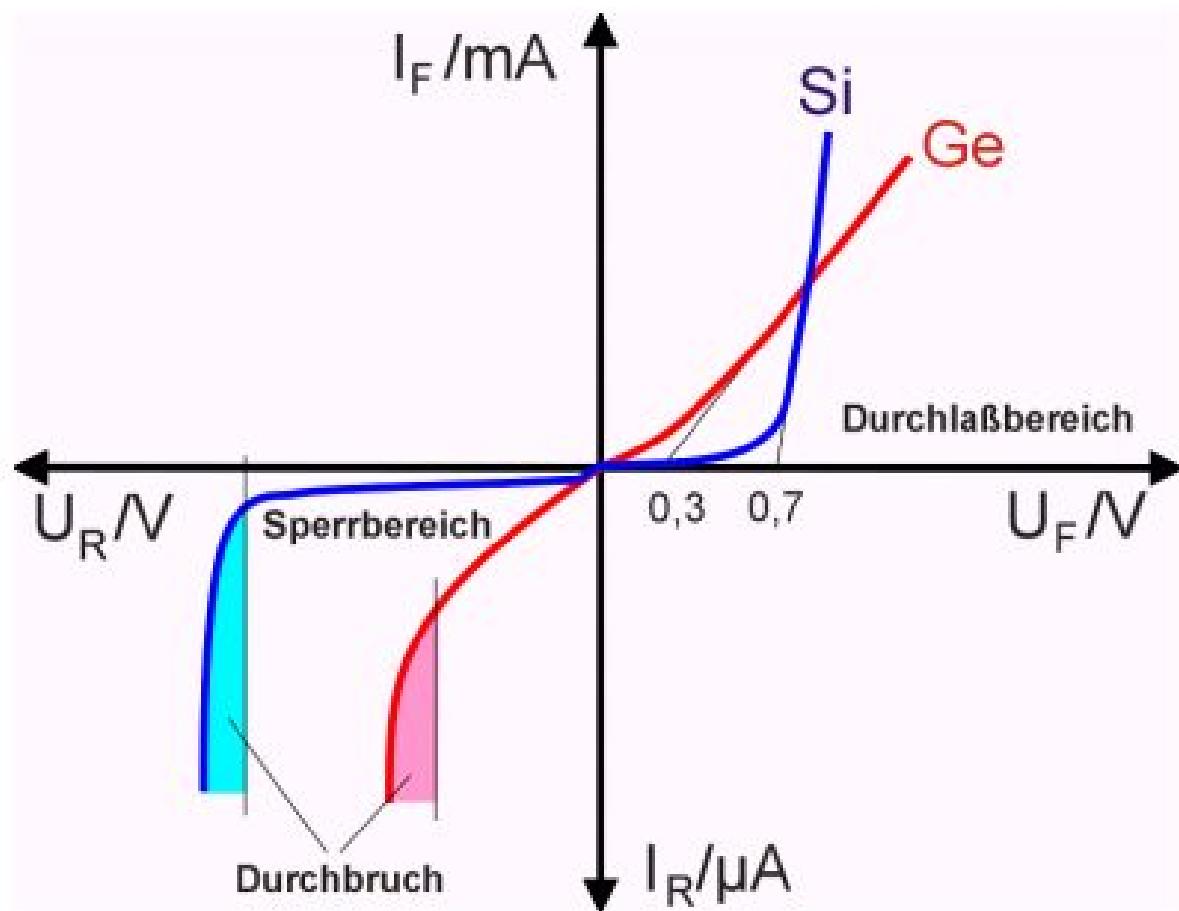
189



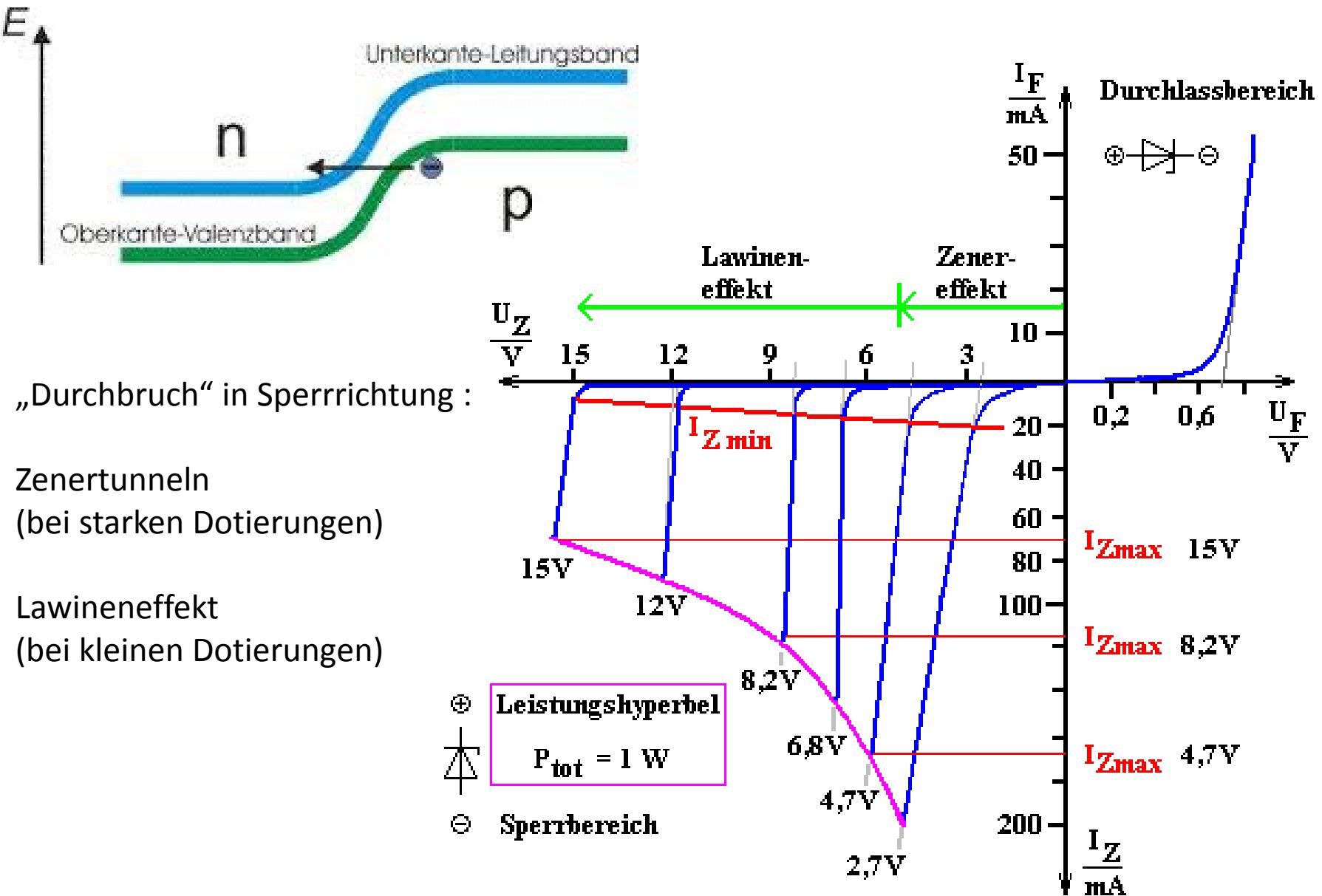
Kopitzki/Herzog, 5. Aufl., S. 181

Kittel, 14. Aufl., S. 602

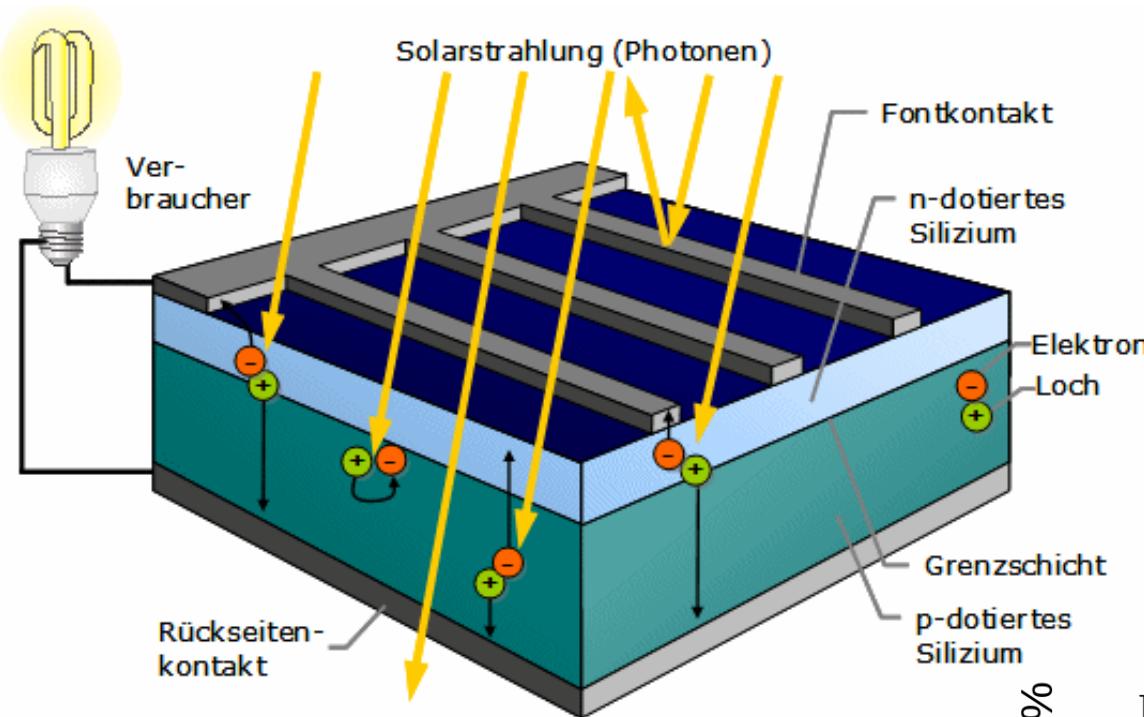
# Vergleich Ge-Si



# Zener Effekt/ Zenerdiode



# Prinzip der Solarzelle



Kleine Bandlücke :

Viele Elektronen im Leitungsband, aber starke Streuverluste

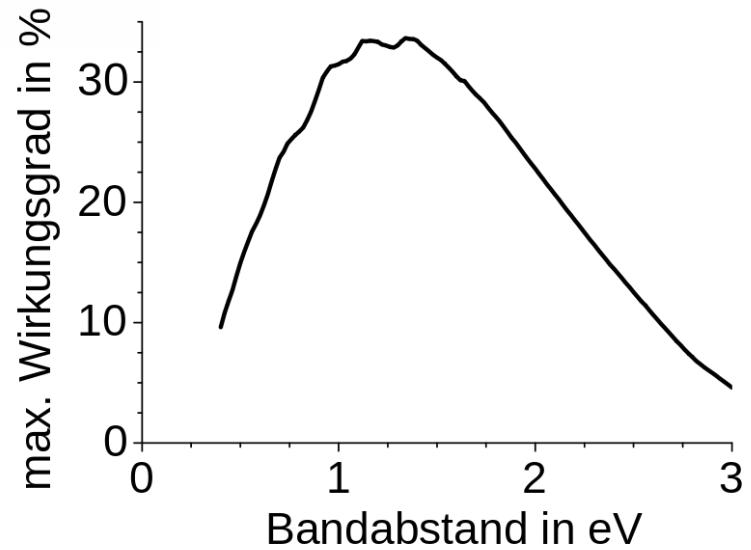
Große Bandlücke :

Wenig Elektronen im Leitungsband, nur das blaue/UV Spektrum wird ausgenutzt

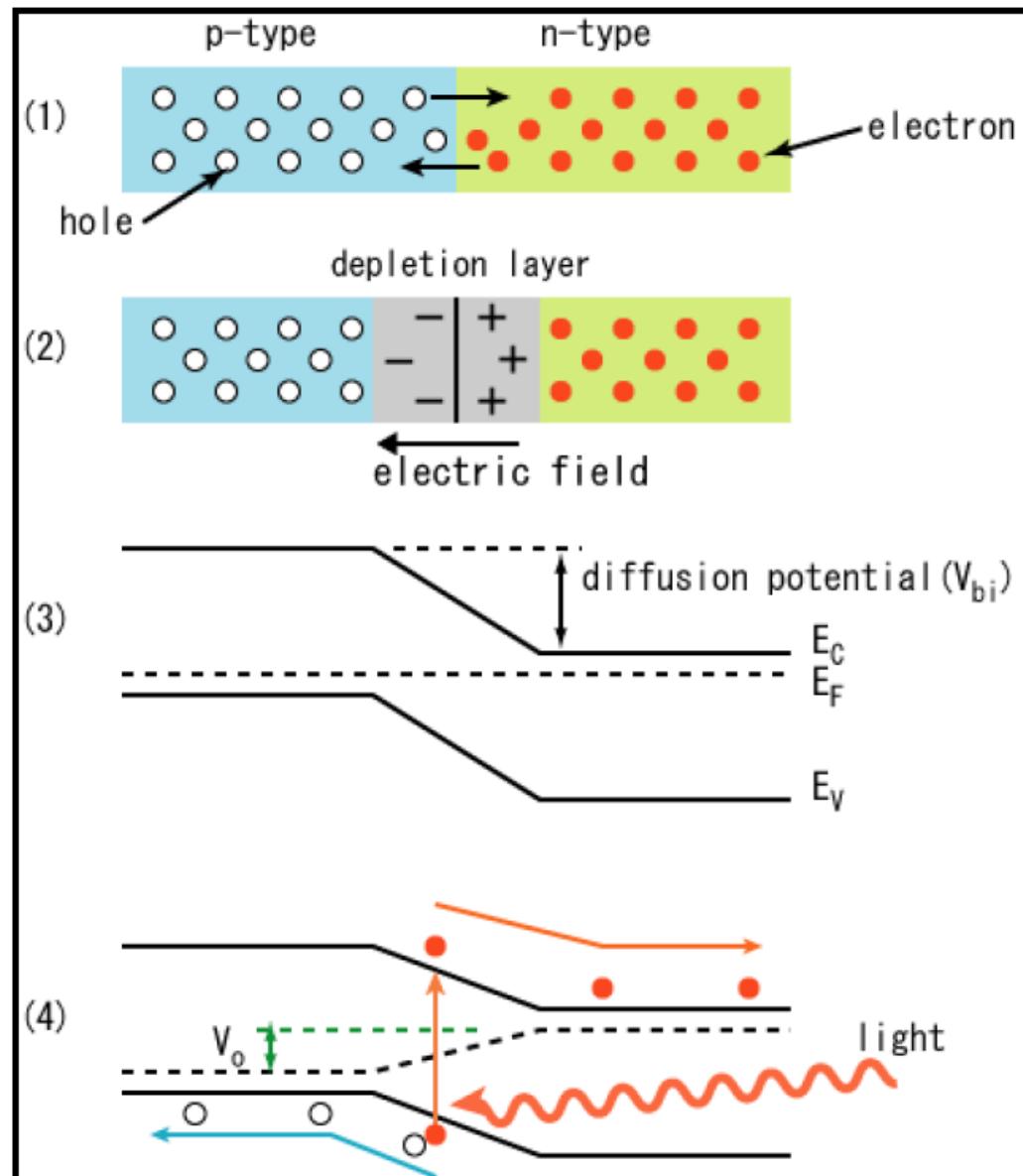
Höhere Wirkungsgrade durch :

Tandemzellen, Konzentratorzellen (z.Zt. ca. 43 %)

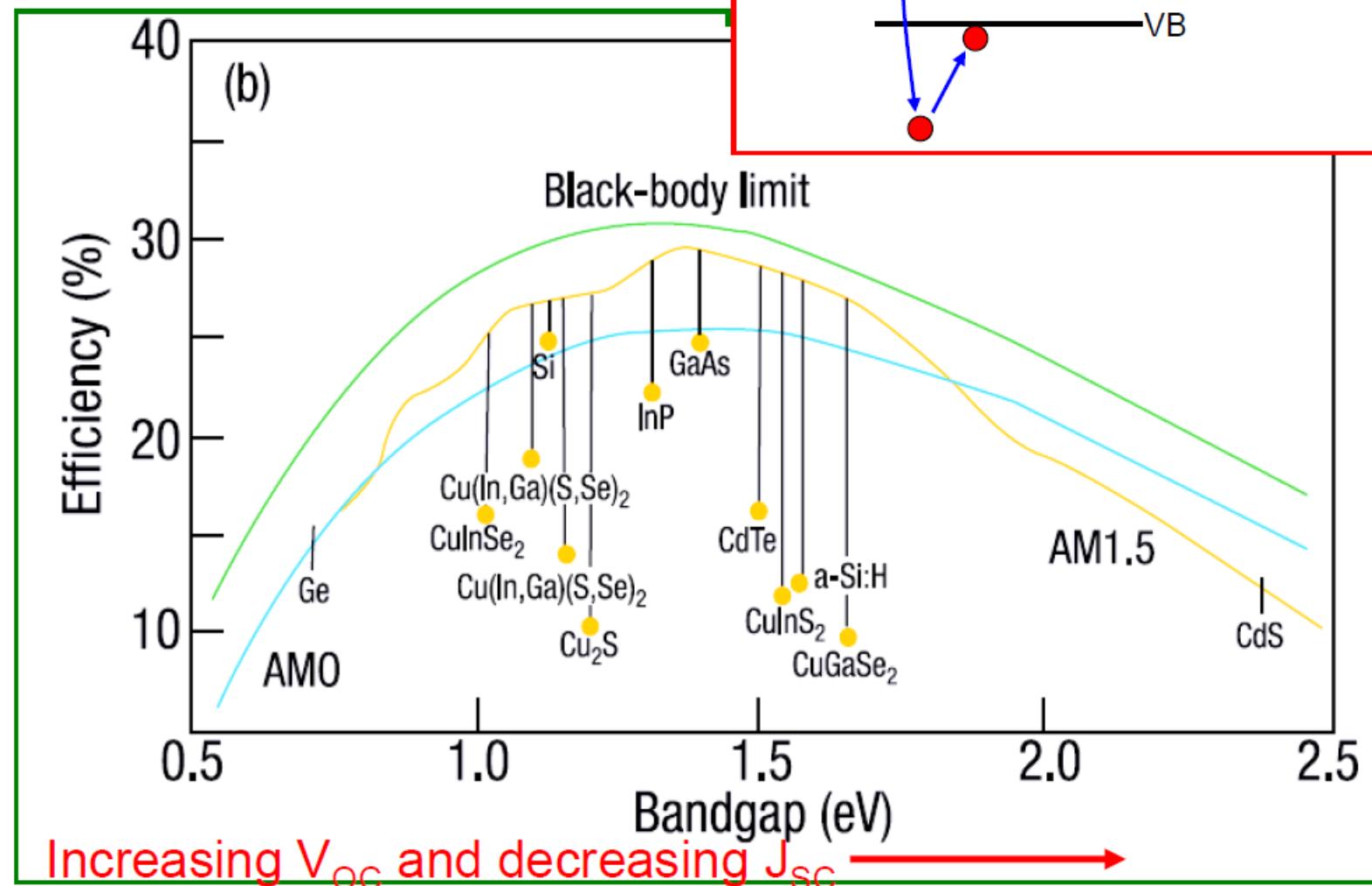
Shockley-Queisser Grenze  
(für einen pn Übergang) :



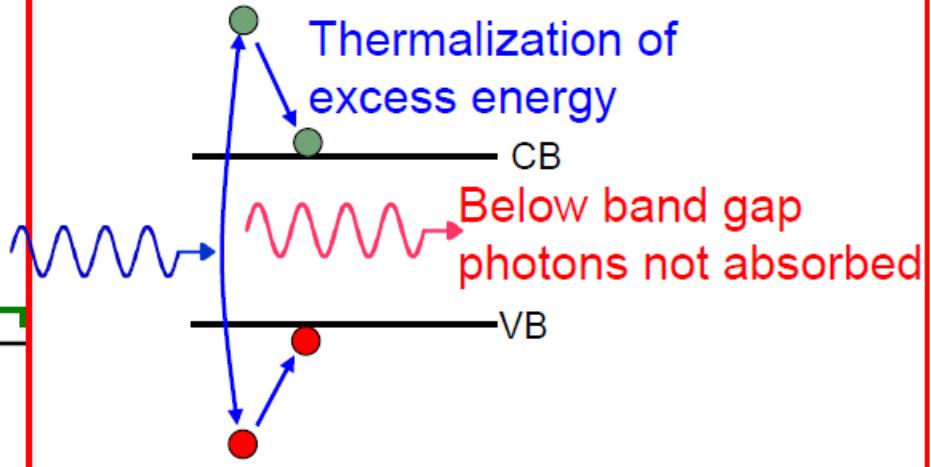
# pn junction PV cell



# Efficiency limits

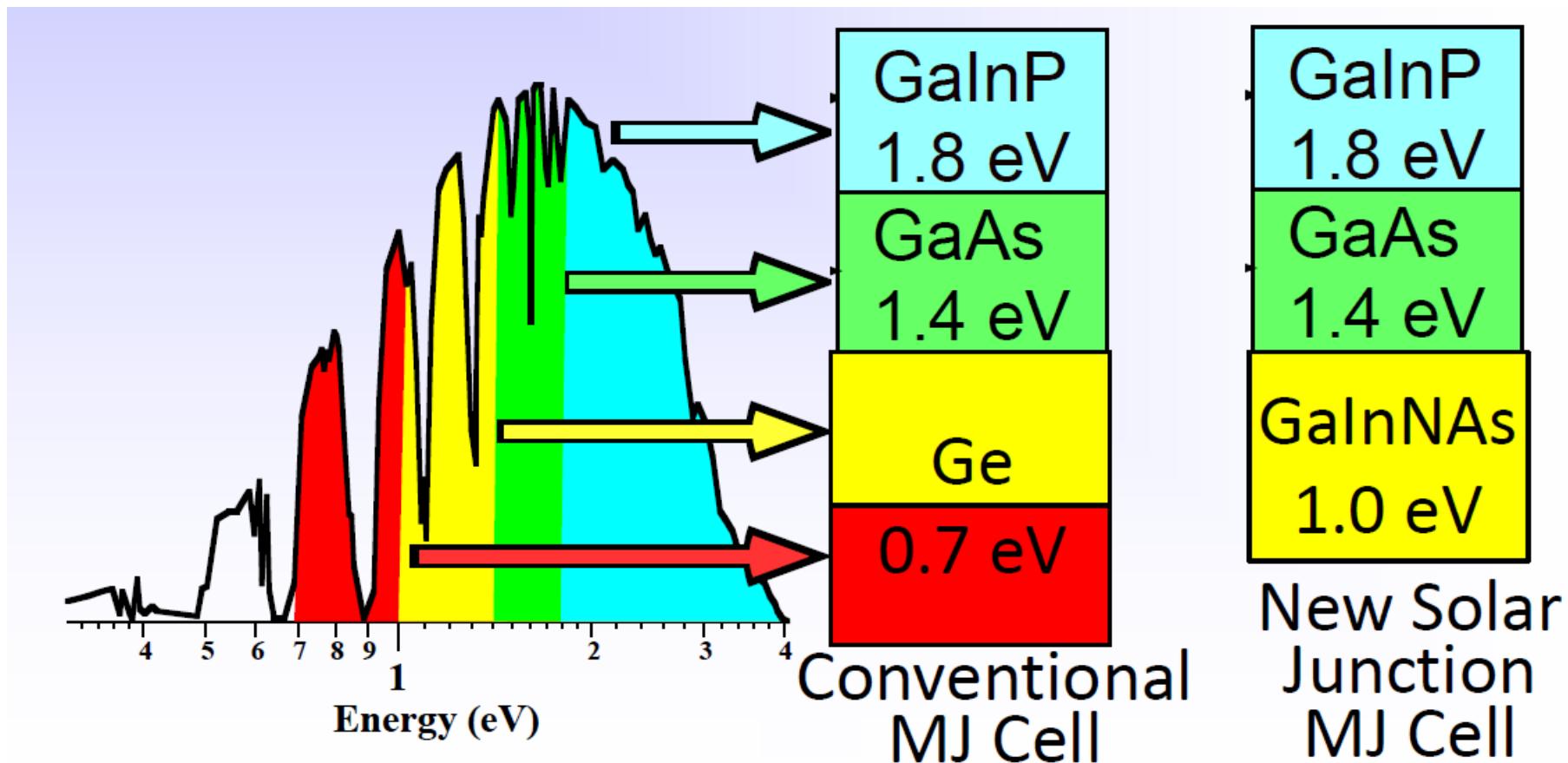


Sources of energy loss



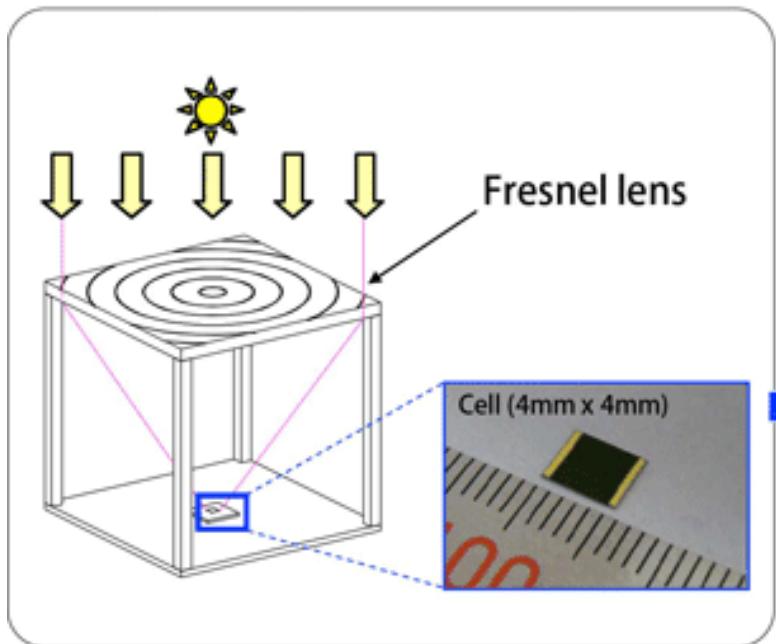
# Tandemzelle / multi junction cell

Bessere Ausnutzung des Sonnenspektrums durch  
Stapelung von Dünnschichtzellen mit unterschiedlichem Bandgap

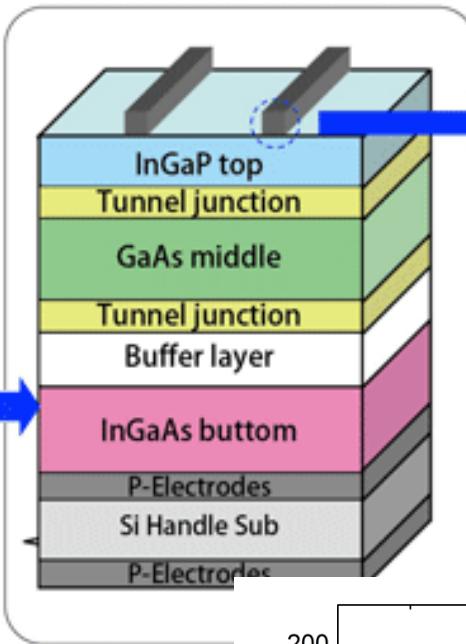


# Aktueller Weltrekord : 4 Junction Concentrator Cell

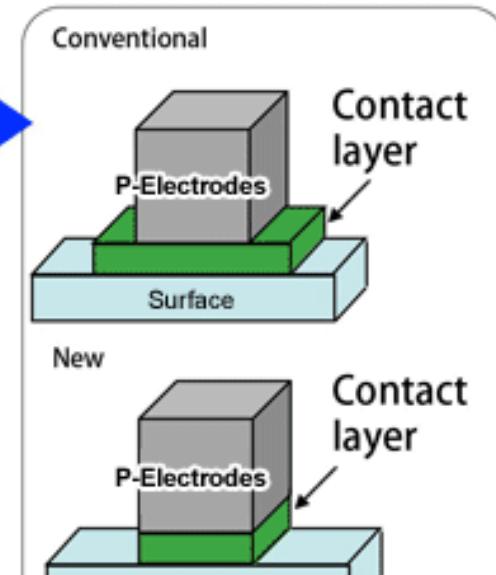
## Concentrator solar cell system



## Structure of a triple-junction compound solar cell

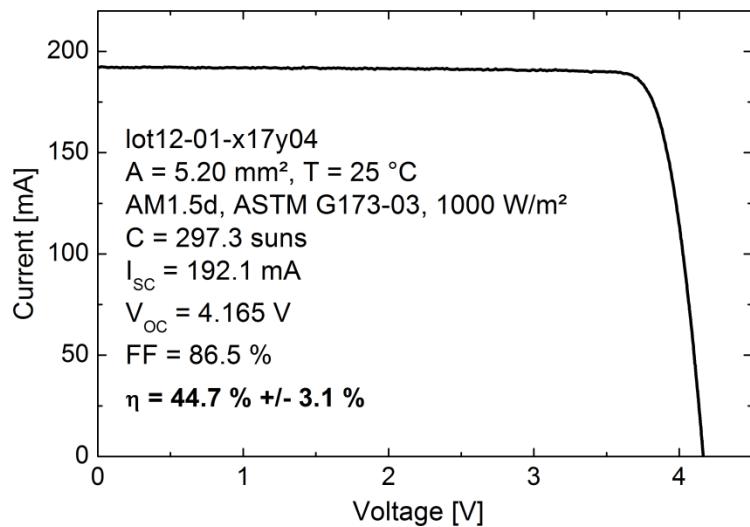


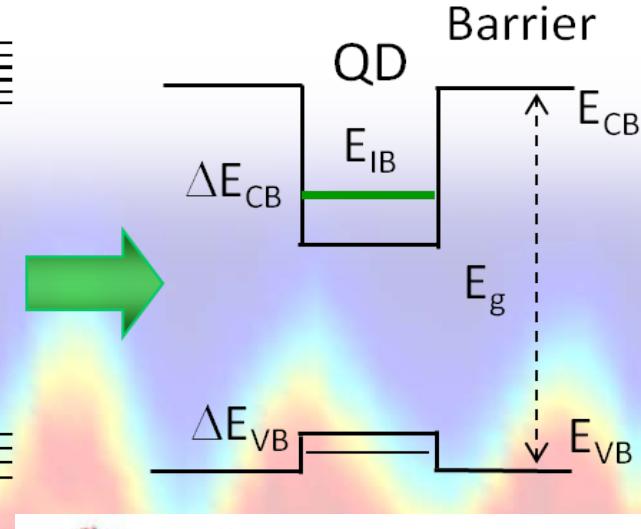
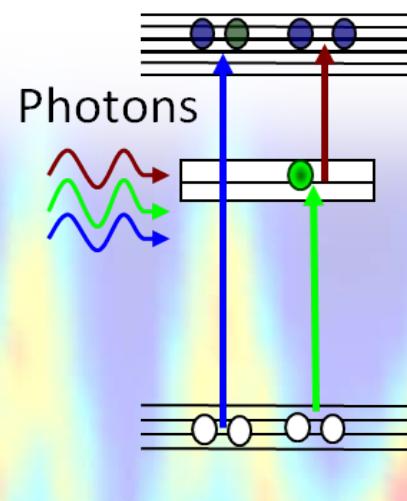
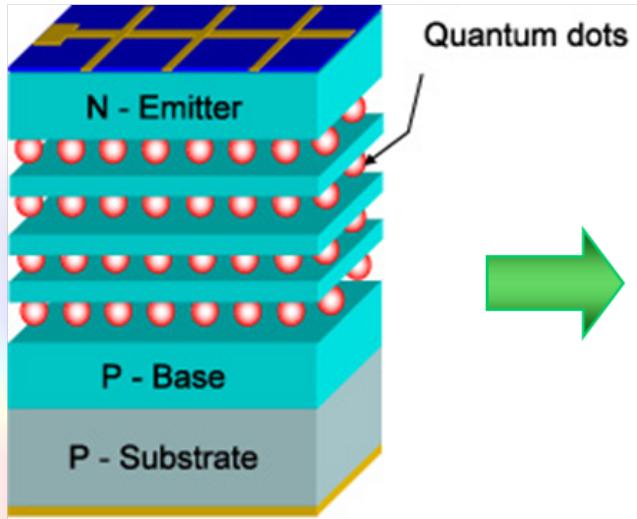
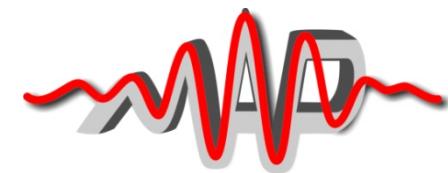
## Comparison with a conventional structure



**Effizienz 44.7 % +/- 3.1 %**

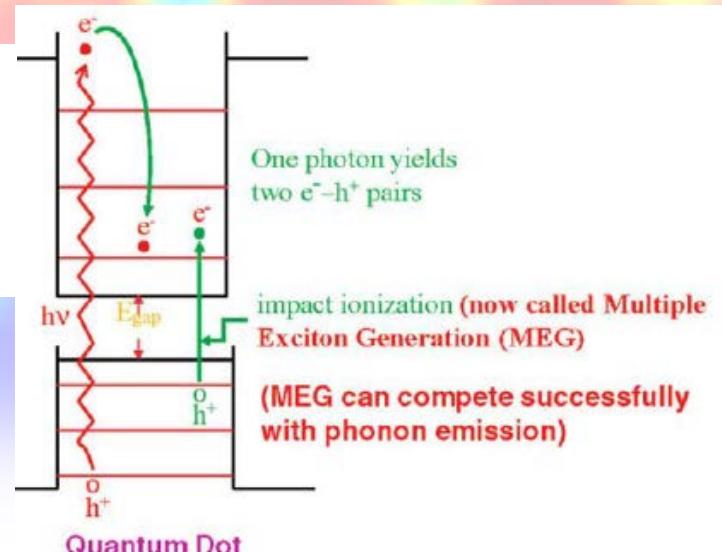
Fraunhofer ISE, September 2013





Quantum dot delivers new sharp energy levels

- Better utilization of infrared photons
- Multi-exciton generation possible



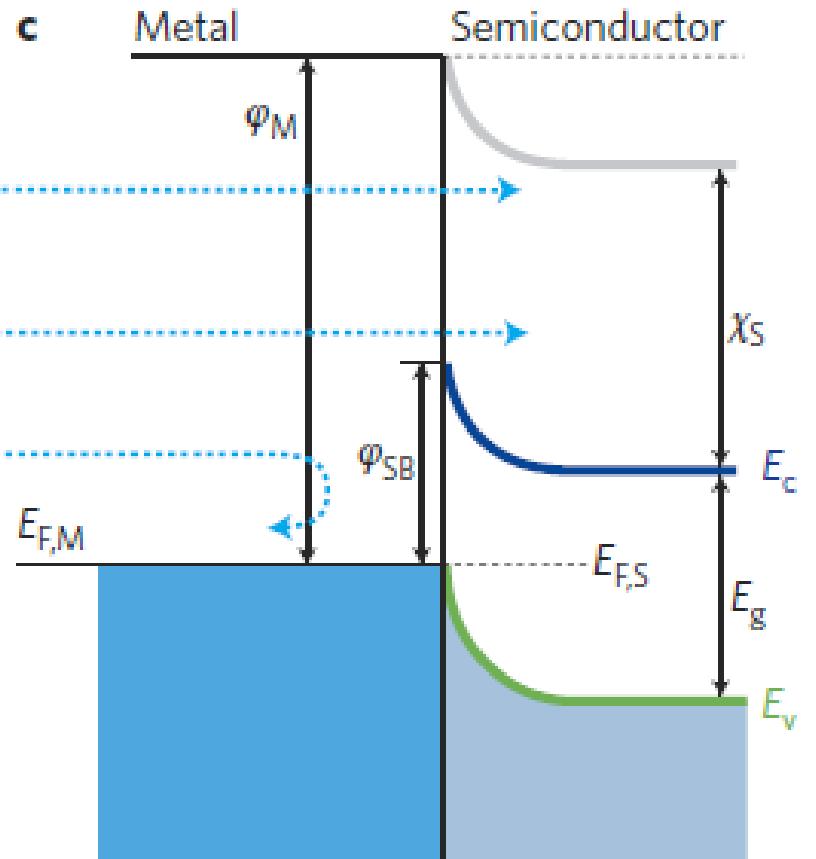
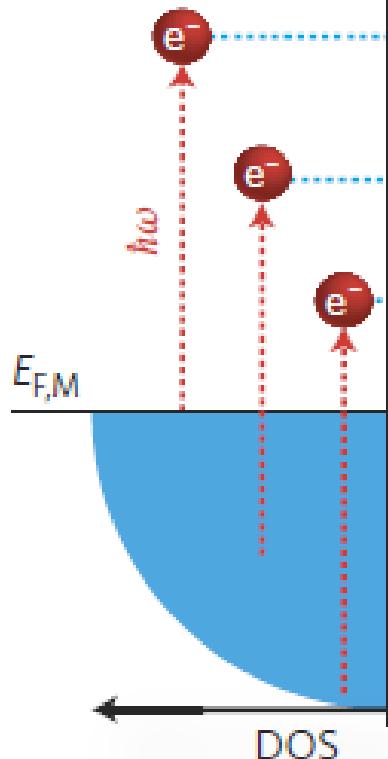
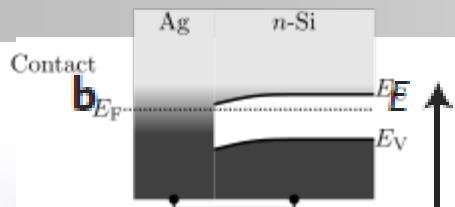
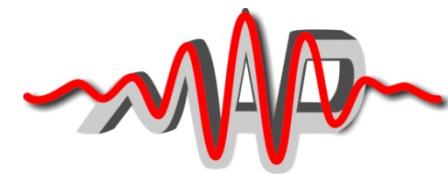
Nearly  
touching

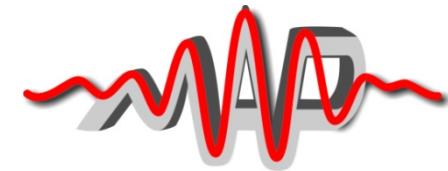
LMU

$\Phi_{Ag}$   $\Phi_{Si}$

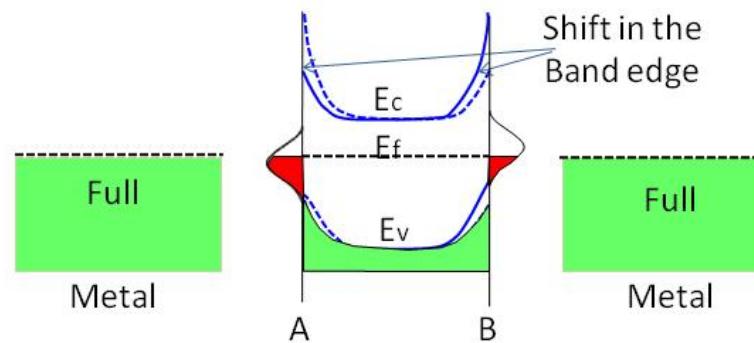
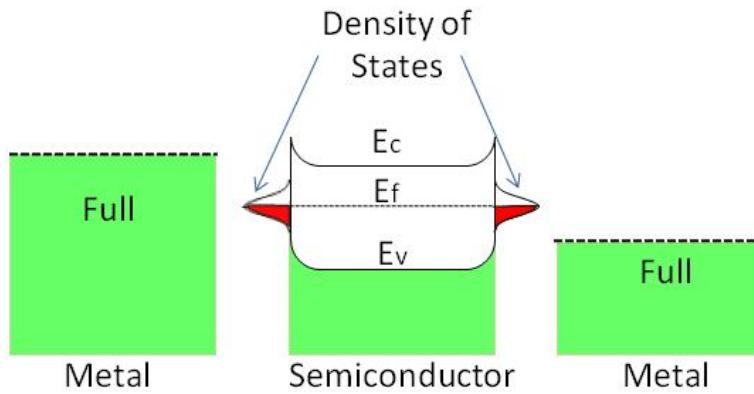
# Hot electron generation and injection through a Schottky contact

Munich-Centre for Advanced Photonics

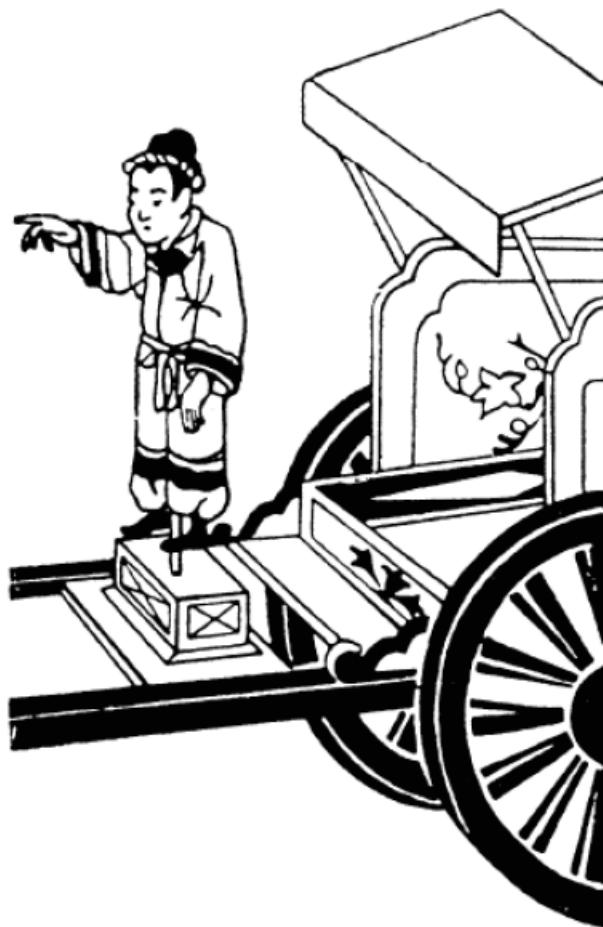




## Fermi-level Pinning

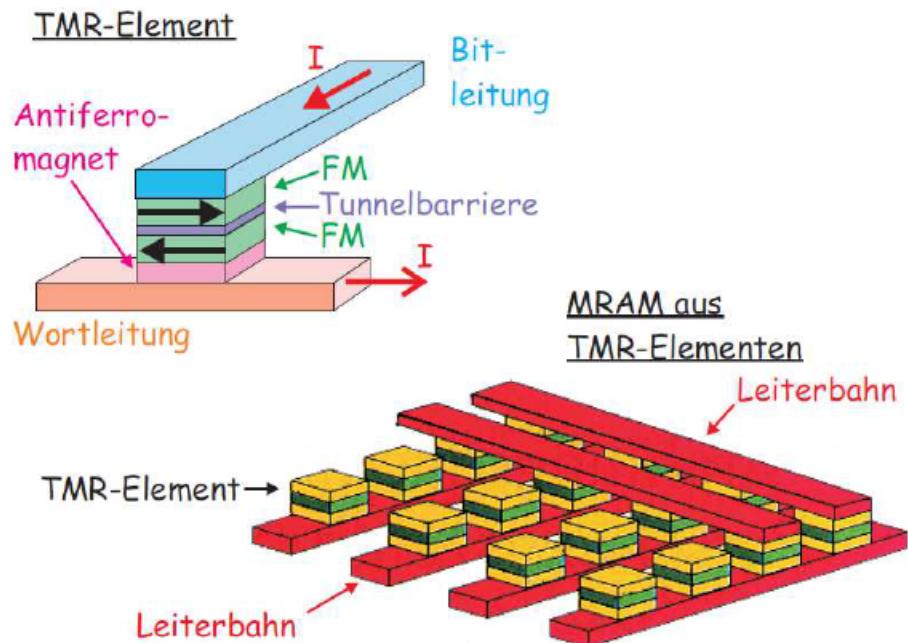


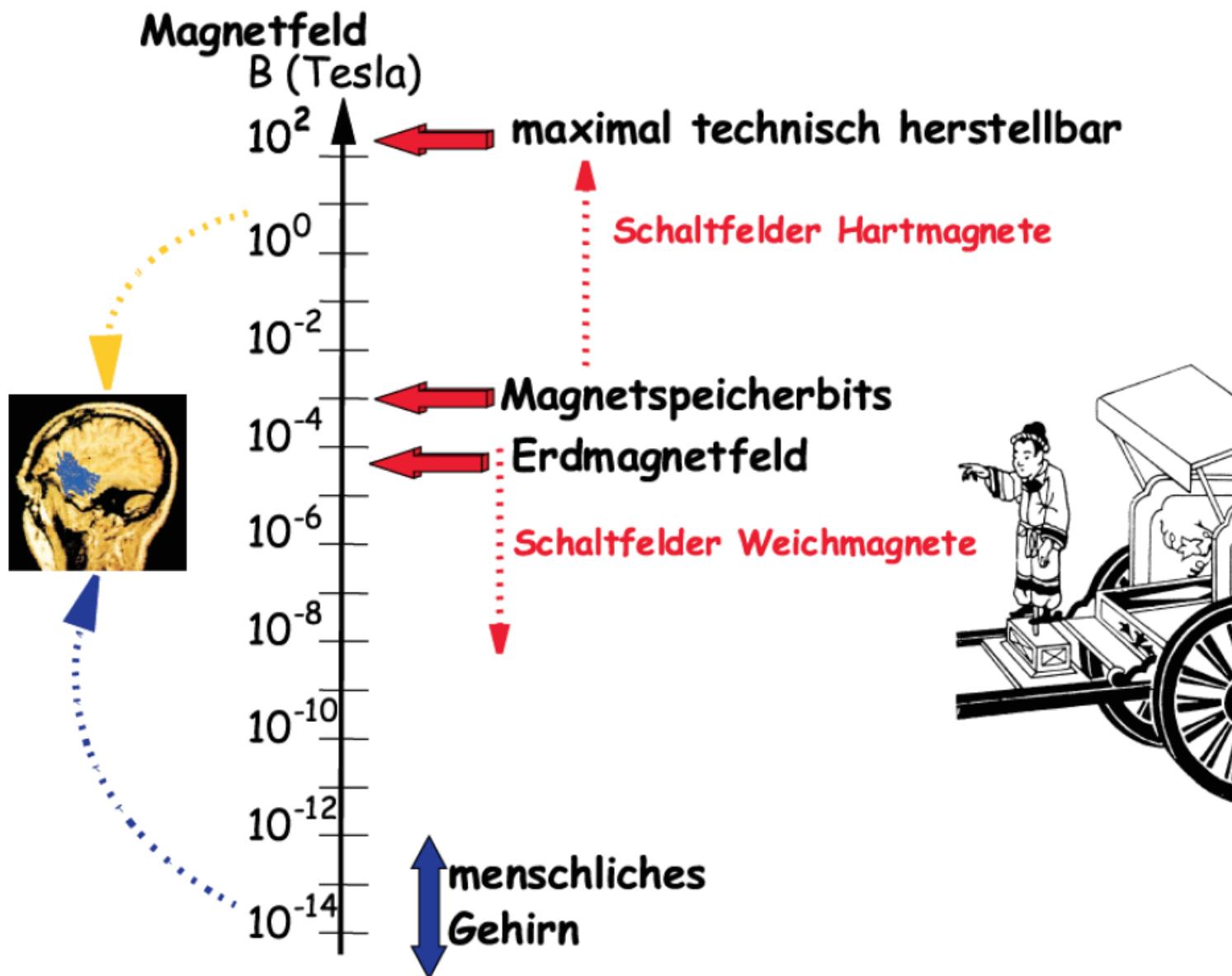
## „Historischer“ und „moderner“ Magnetismus



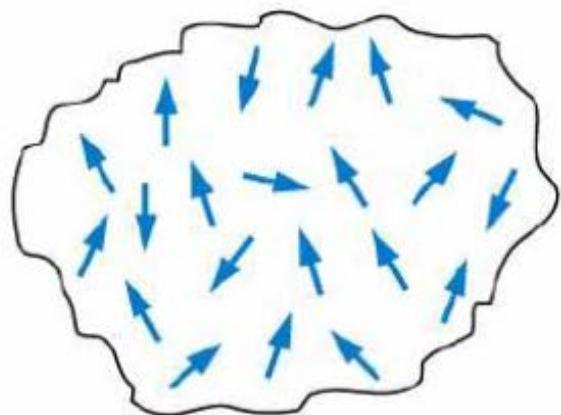
chinesischer "Südweiser"  
tschi-nan (ca. 1000 v.Chr.)

## Magnetic-RAM (MRAM)

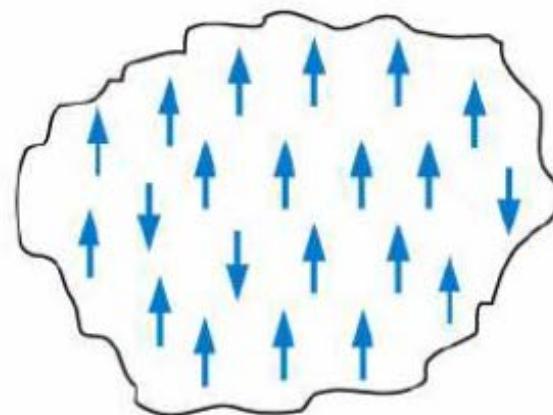




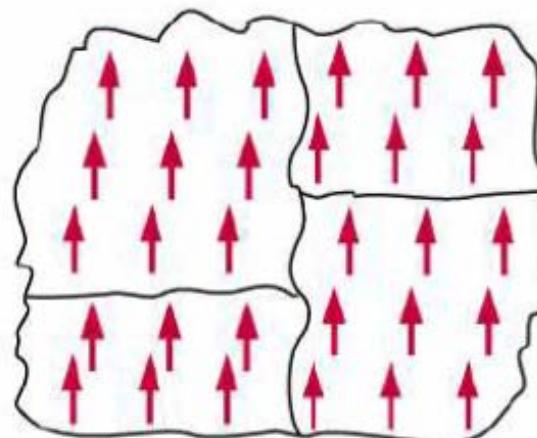
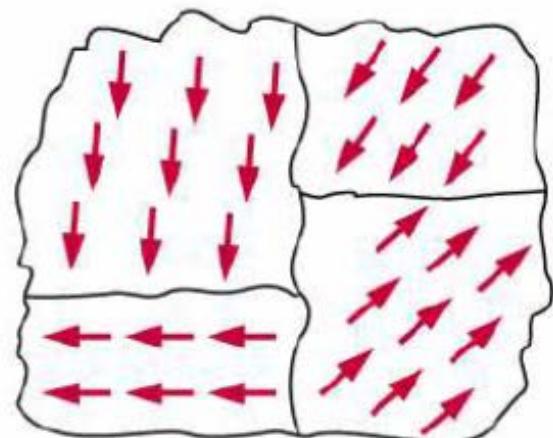
Magnetic field absent



In presence of magnetic field

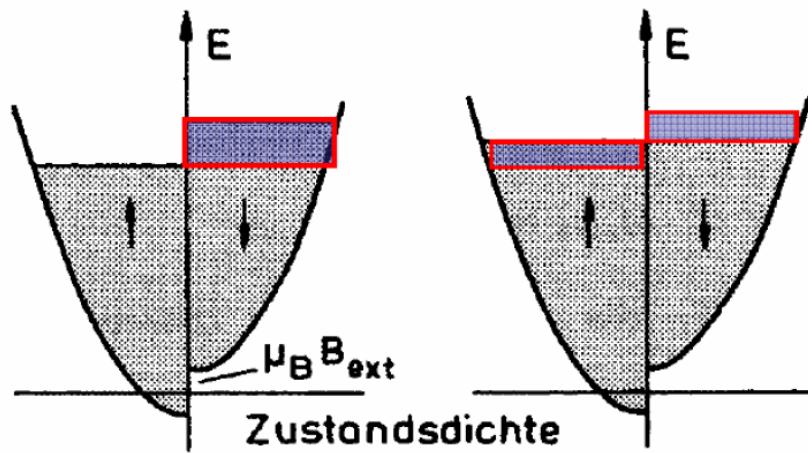


Paramagnetism

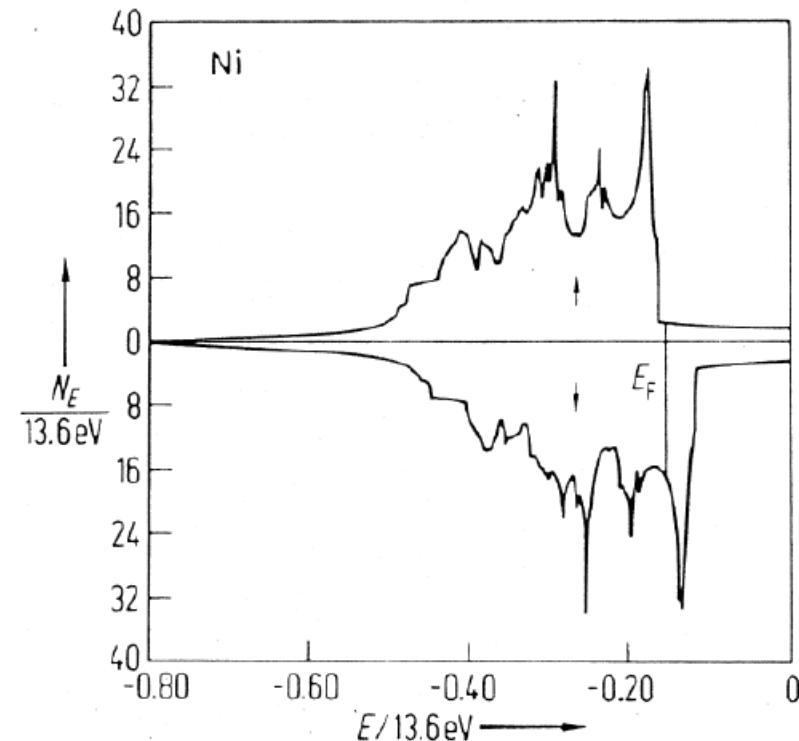
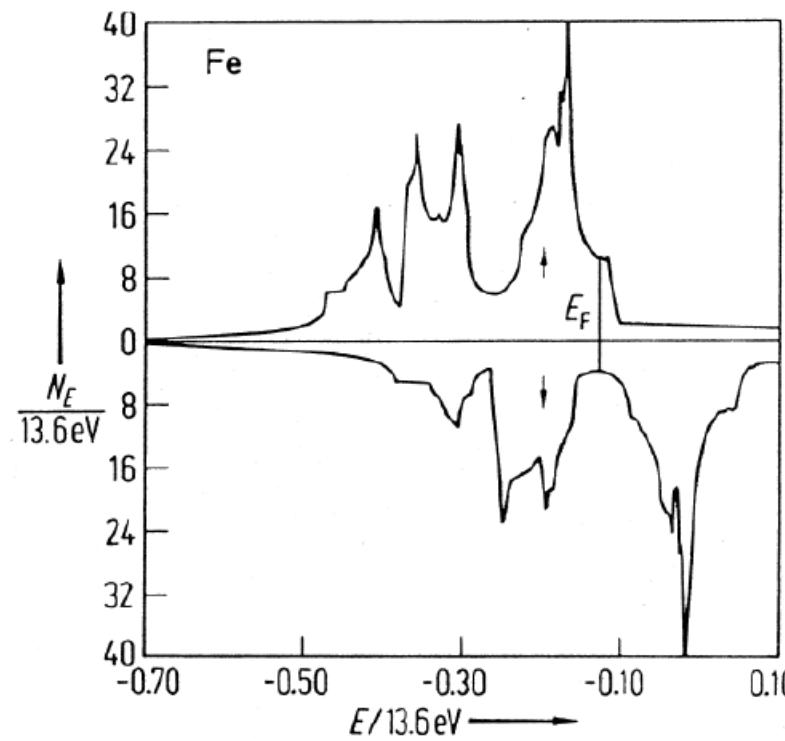


Ferromagnetism

## Paulischer Paramagnetismus

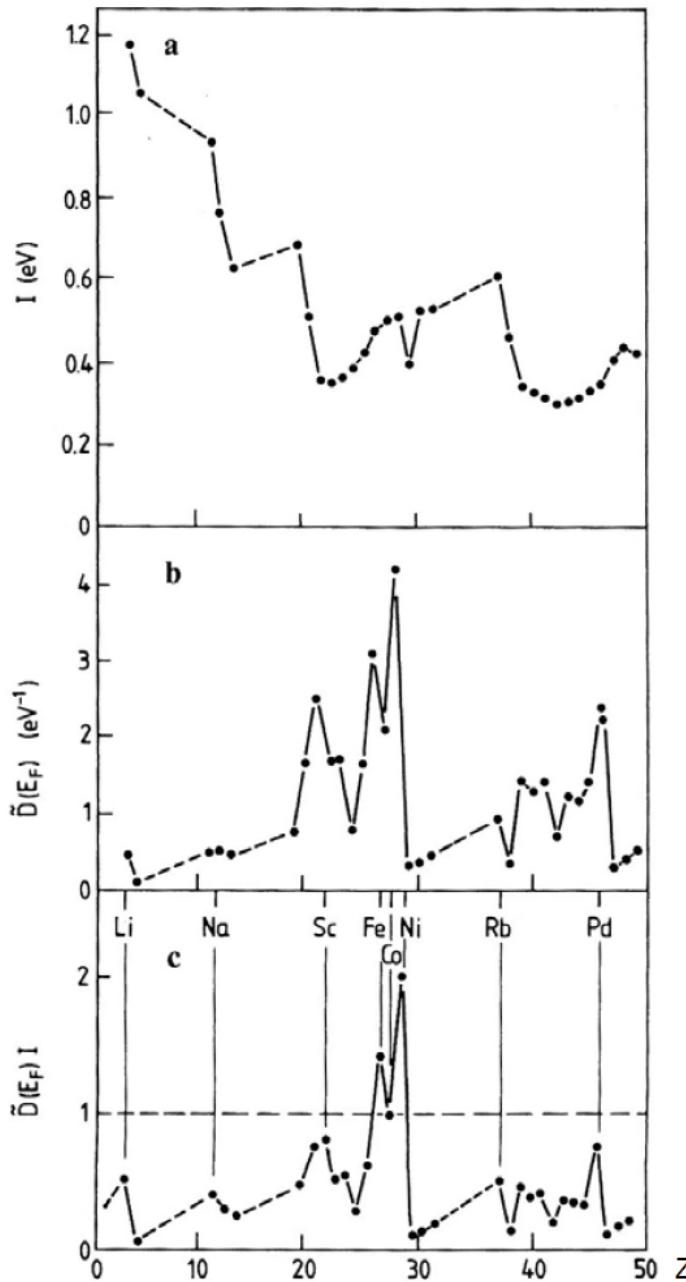


Zustandsdichte der 3D Ferromagneten



## Stoner Criterion for Ferromagnetism:

$$I \cdot \tilde{D}(E_F) > 1$$



$I$  = Exchange integral

$\propto$  Energy reduction per electron

$\tilde{D}(E_F)$  = Density of states at  $E_F$   
(per atom, per spin)

$\propto$  Number of electrons  
reducing their energy

$$I \cdot \tilde{D}(E_F)$$

Only Fe, Ni, Co pass the Stoner criterion.  
These are indeed the only ferromagnets in  
this range of atomic numbers  $Z$ .

Magnetoelektronik = Magnetismus  
+  
Elektronik ?



## Halbleiterelektronik

→ Transistor

- Prozessoren
- schnelle Speicher

Geschwindigkeit

MINIATURISIERUNG

## magnetische Speicher



magnetische "bits"

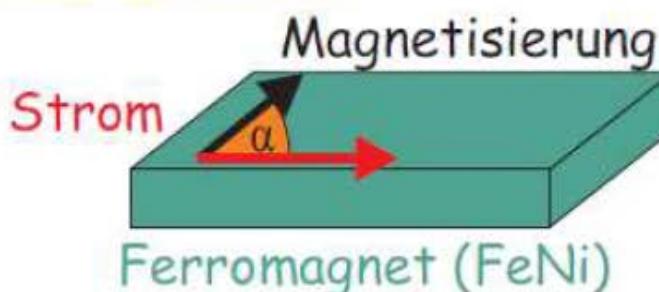
- Festplatten
- Magnetbänder, ...

Speicherdichte

# Magnetoresistive Effekte

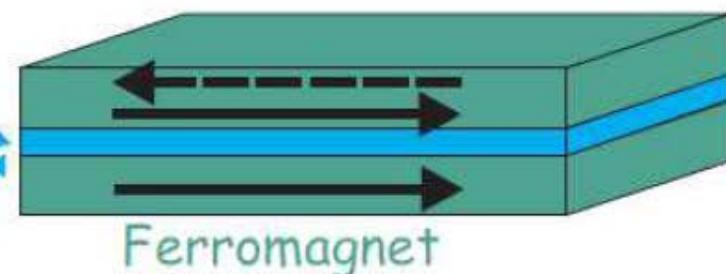
- anisotroper Magnetowiderstand:

AMR



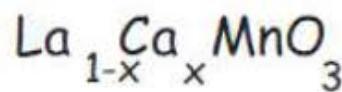
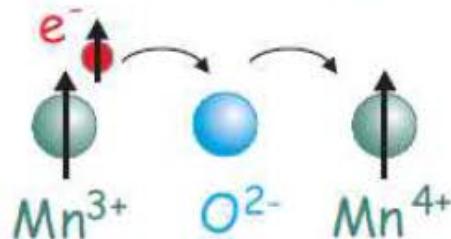
- Riesenmagnetowiderstand: **GMR**  
(giant magnetoresistance)

Metall  
Isolator

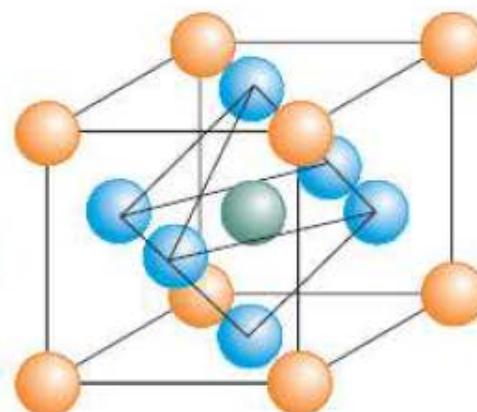


- Tunnelmagnetowiderstand: **TMR**

- kolossal Magnetowiderstand: **CMR**



Ca, La, Ba



## Drehwinkelsensor (berührungs frei, z.B. Automobil)

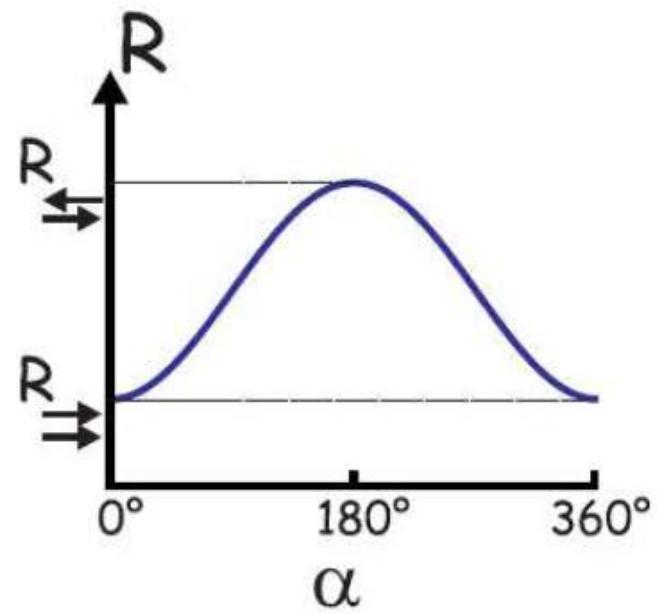
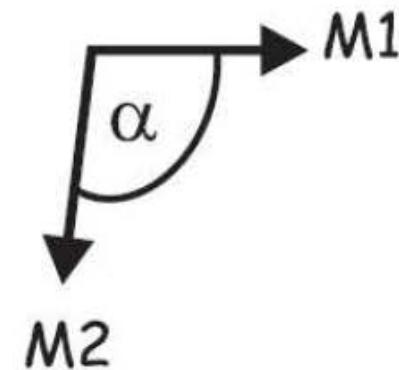
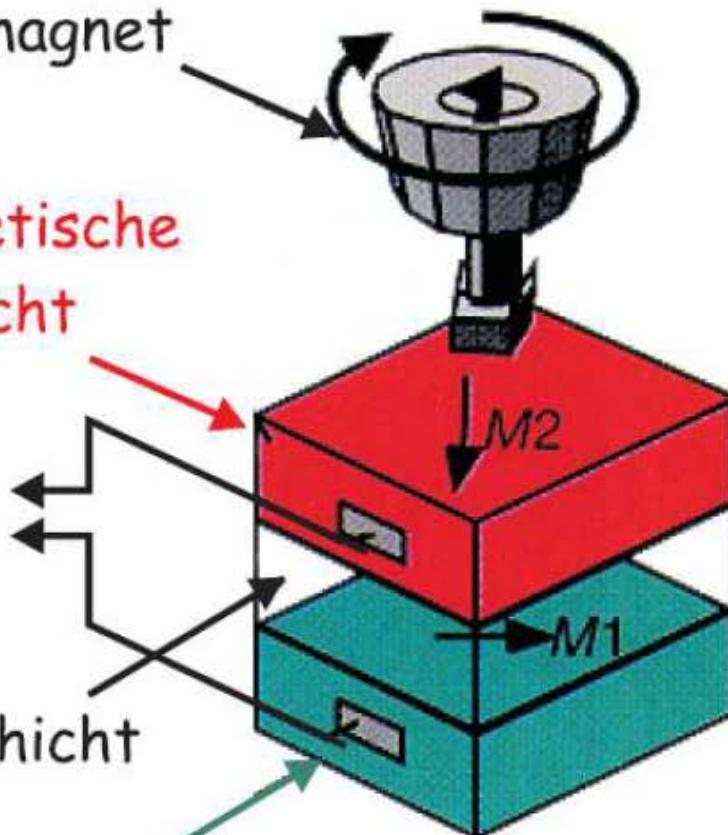
rotierender  
Permanentmagnet

weichmagnetische  
Sensorschicht

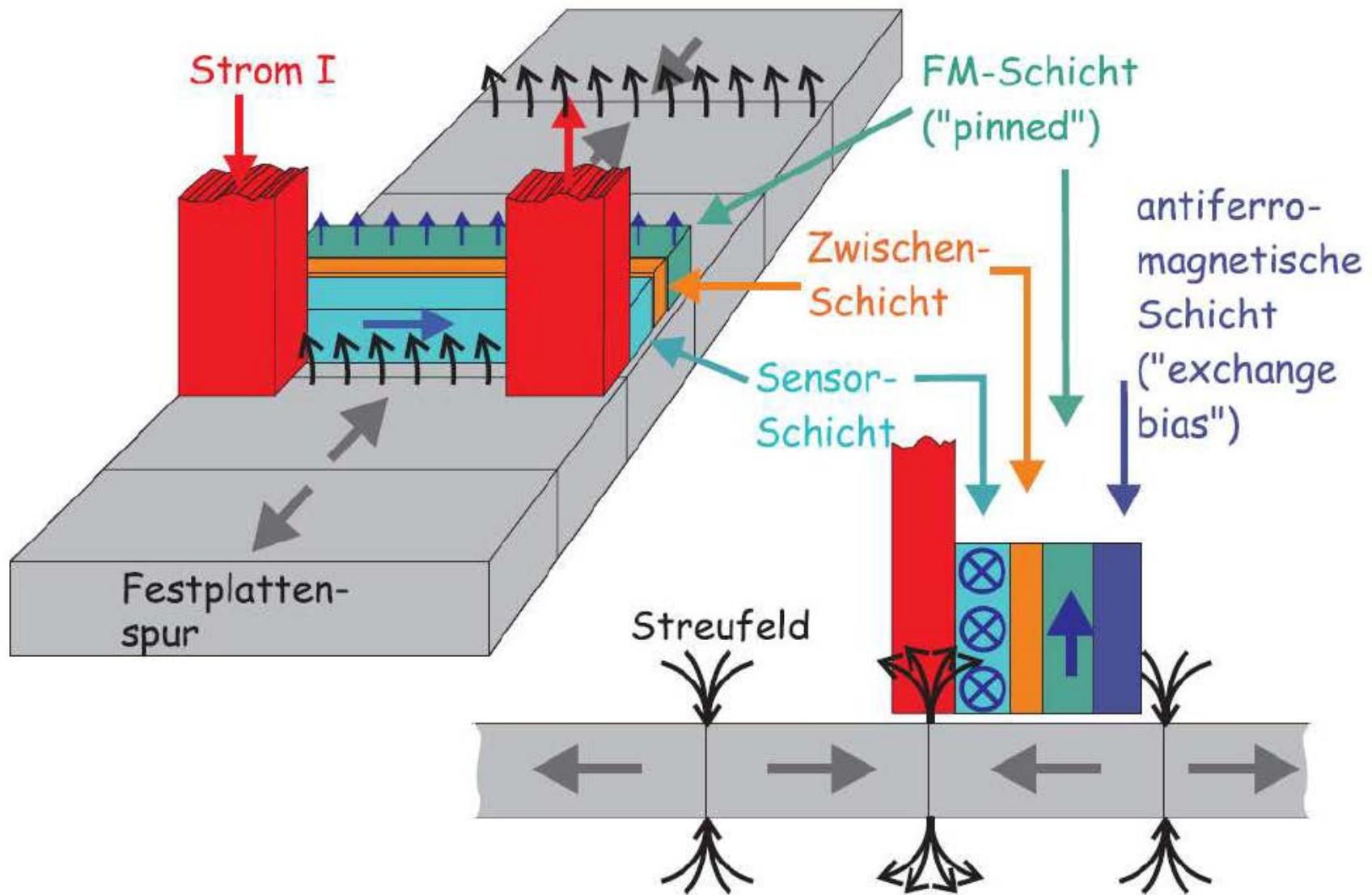
Auswerte-  
Elektronik

Zwischenschicht

hartmagnetisches  
Basisschichtsystem

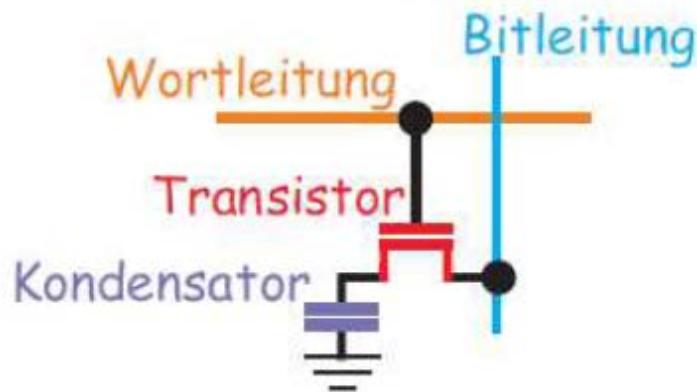


## GMR Lesekopf (Festplatten)

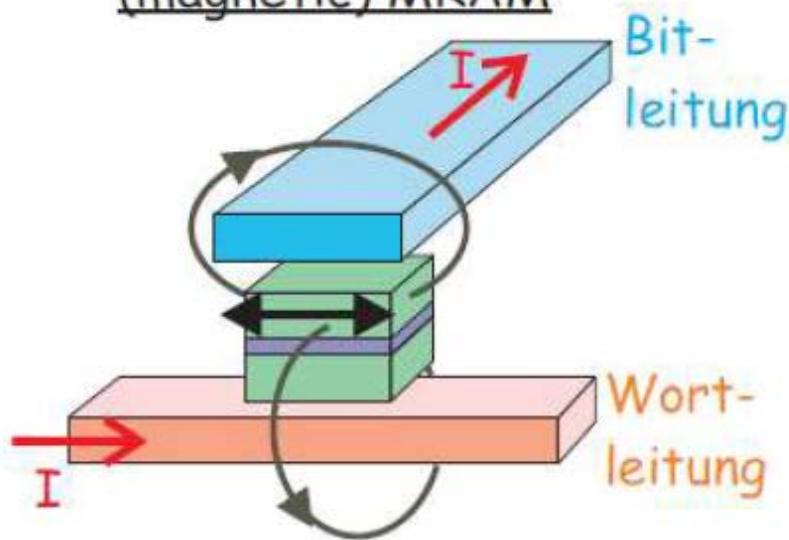


# RAM = Random Access Memory

(dynamic) DRAM



(magnetic) MRAM

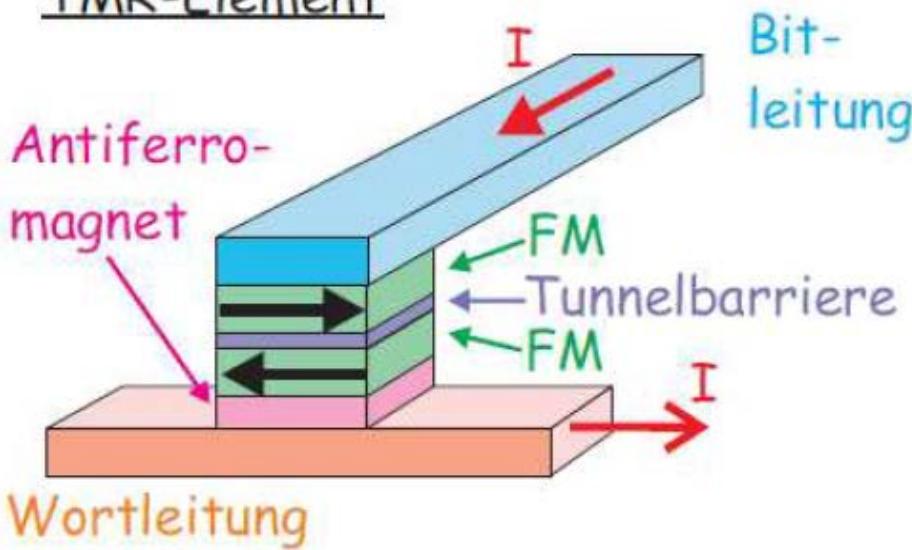


- kurze Zugriffszeiten (~50ns)
- flüchtig!  
"Auffrischen"  
(im ~10ms-Takt)

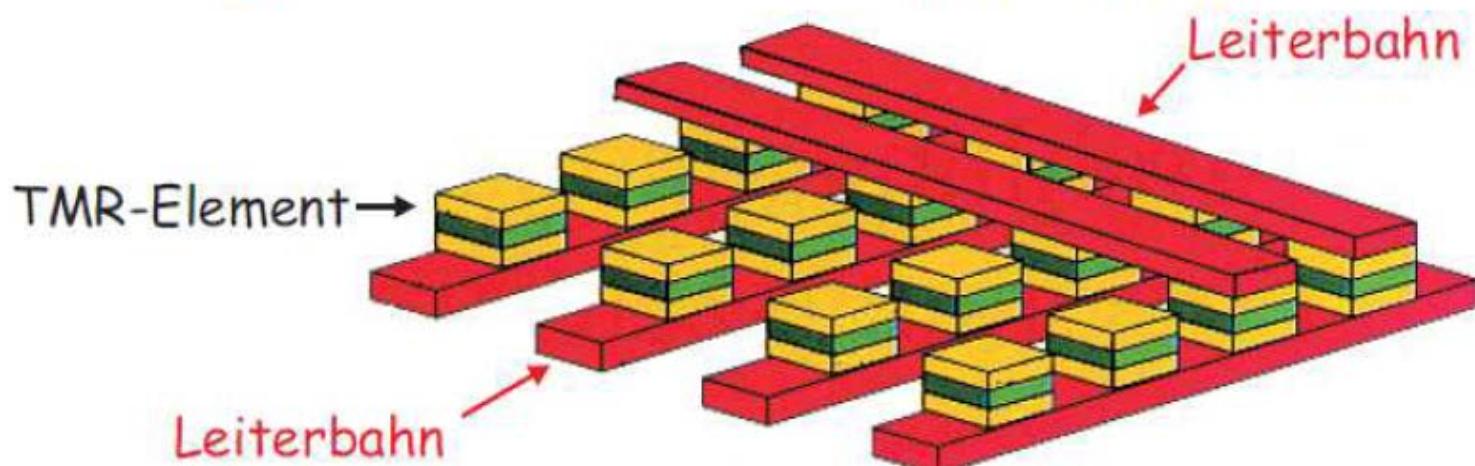
- kurze Zugriffszeiten (~50ns)
- nicht-flüchtig!

# Magnetic-RAM (MRAM)

TMR-Element

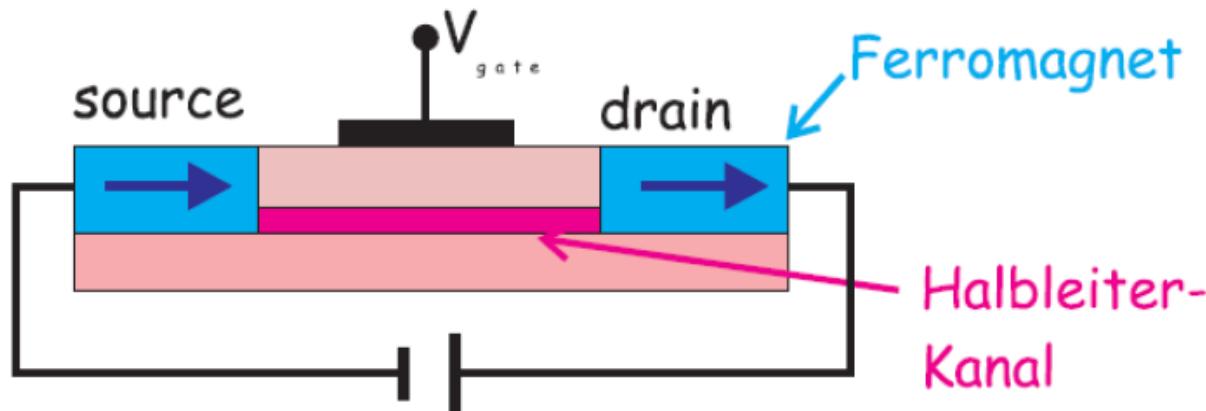


MRAM aus  
TMR-Elementen

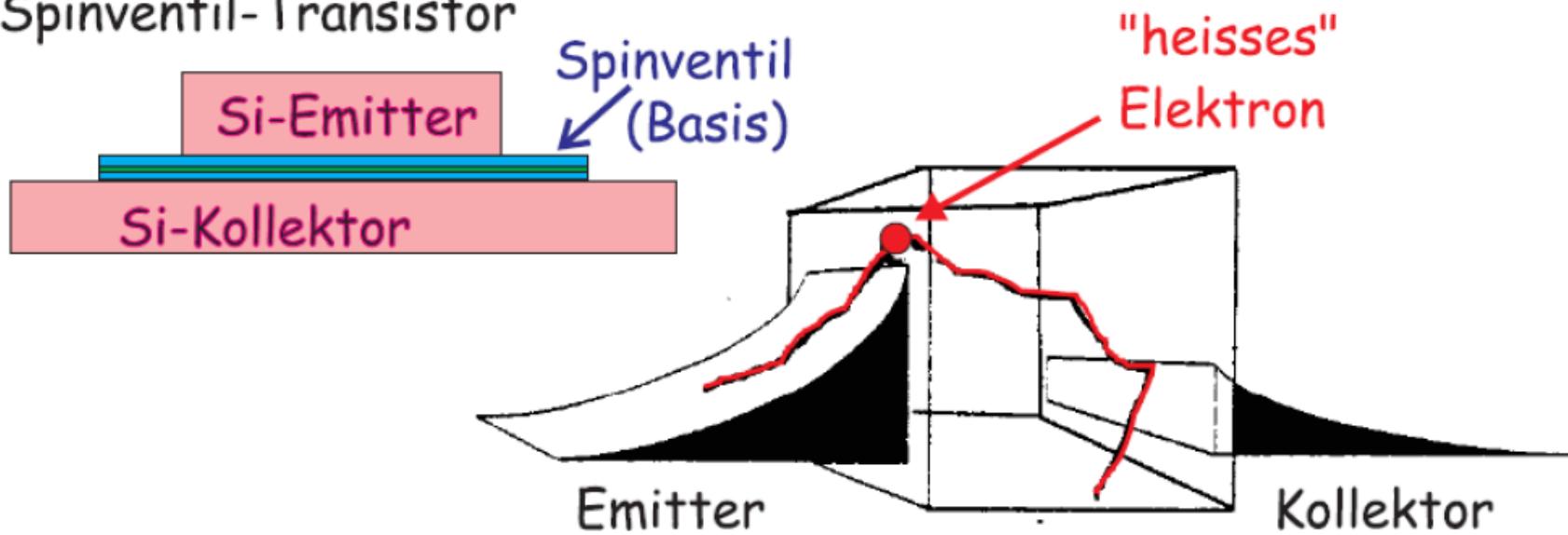


## Konzepte für zukünftige Spin-Transistoren

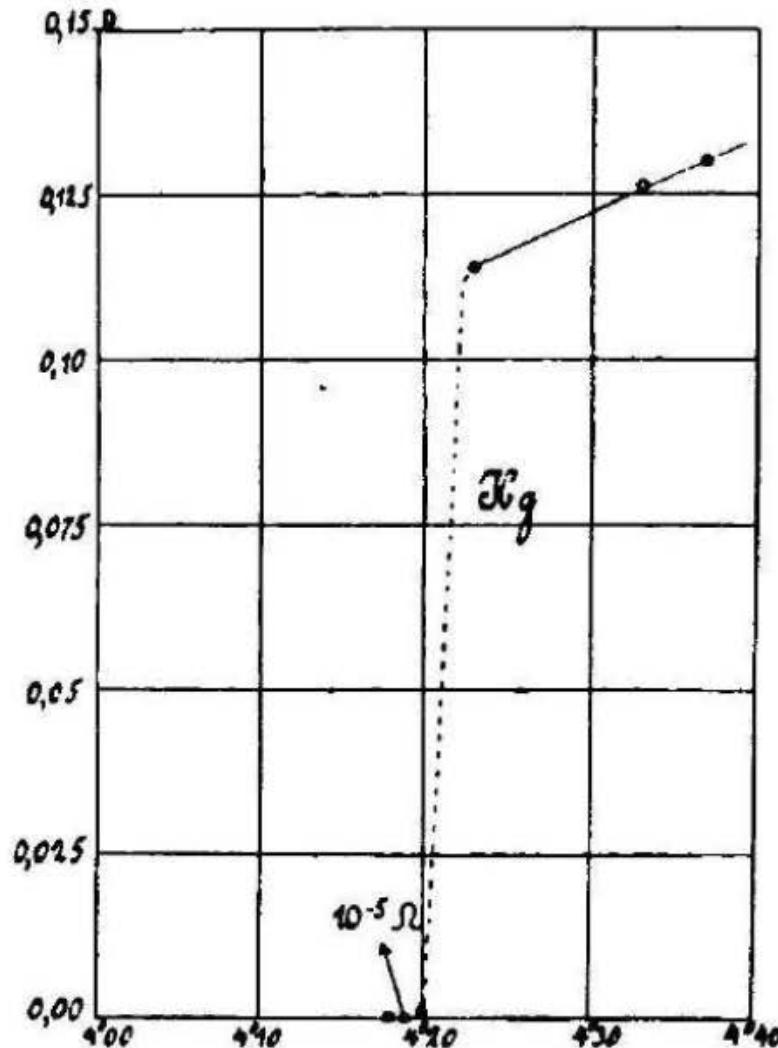
- Spin-FET (Feldeffekttransistor)

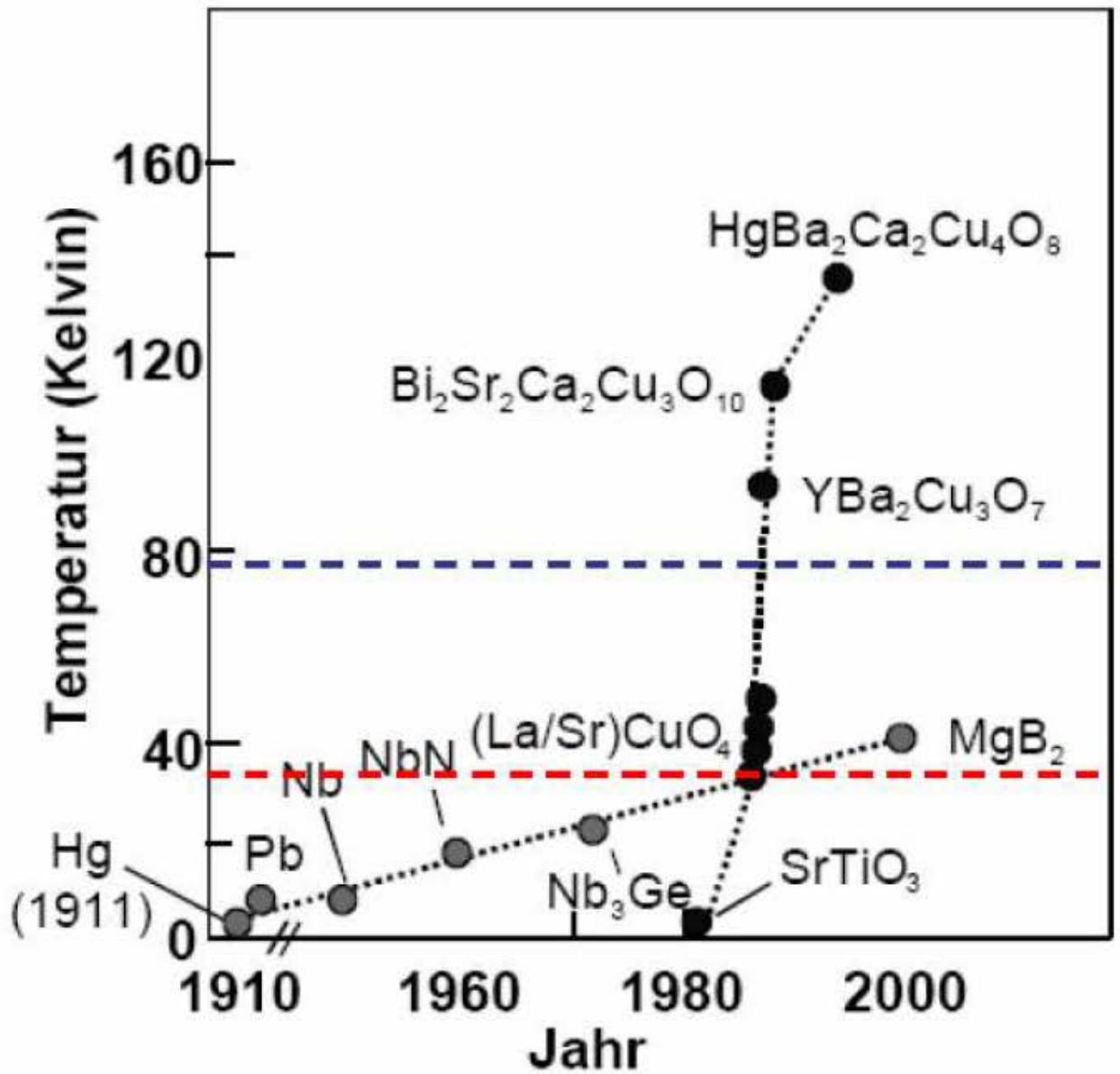


- Spinventil-Transistor



# Widerstand von Quecksilber: Entdeckung der Supraleitung (Kamerlingh Onnes 1911)



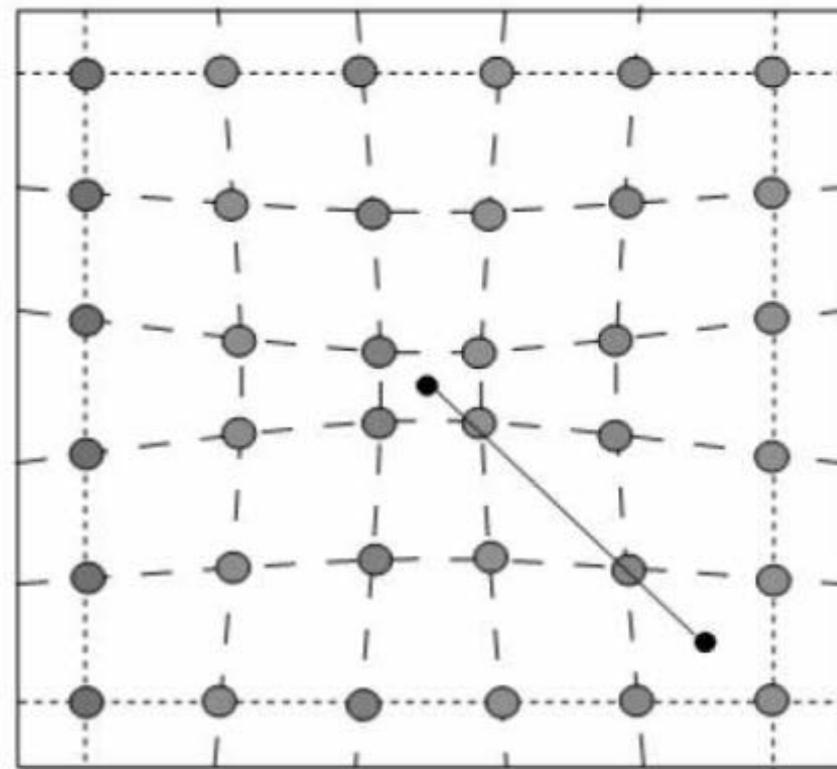
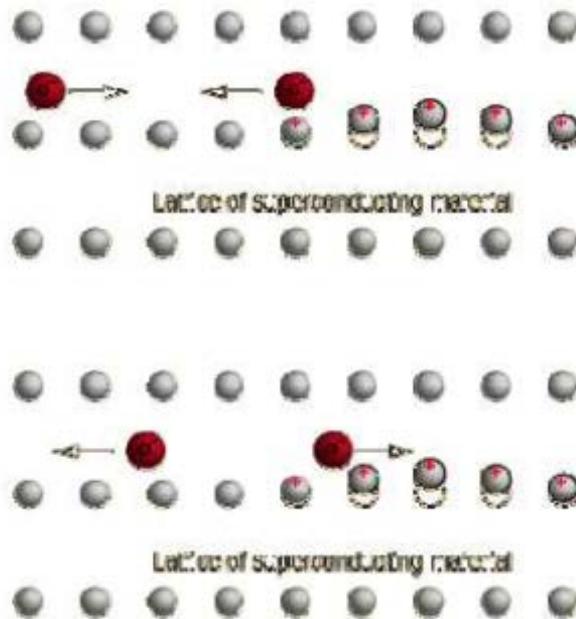


Flüssig-N<sub>2</sub>

He-Kompressor

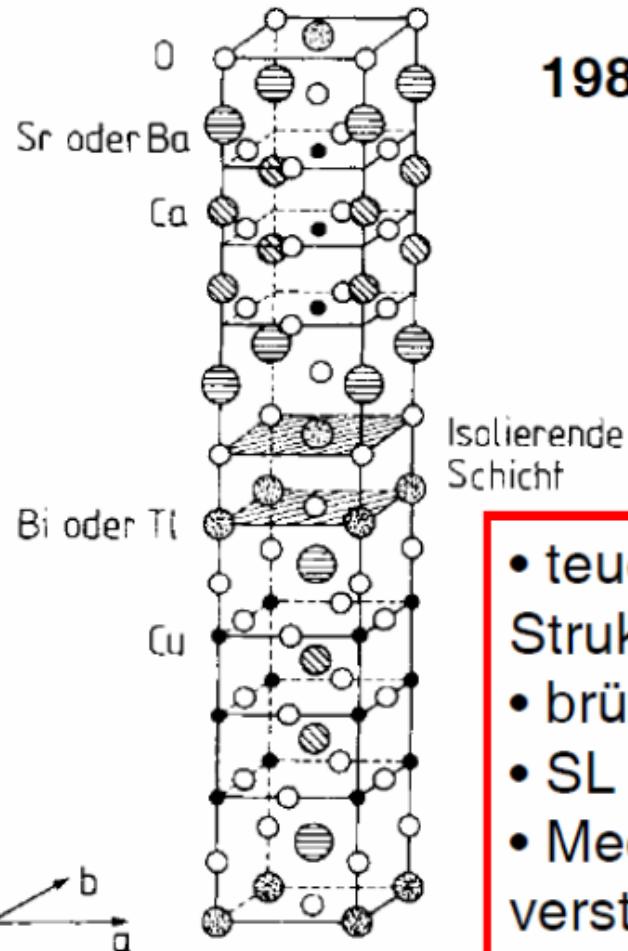
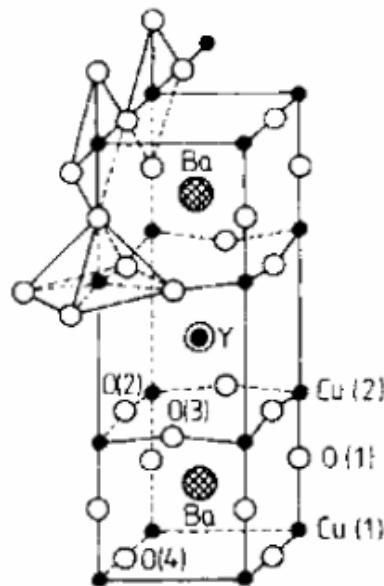
# Klassische Supraleitung : BCS Theorie

## Cooper-Paare



Wechselwirkung durch Phononen über  **$10^4$  Gitterkonstanten!**

# Hochtemperatur-Supraleiter



1986: Bednorz und Müller

$$T_{c,\max} \approx 135 \text{ K}$$

Rekord :  $T_c = 138 \text{ K}$   
 $\text{Hg}_{0,8}\text{Tl}_{0,2}\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_8$

- teuer (komplizierte Strukturen)
- brüchig
- SL bei Stickstofftemperatur
- Mechanismus der SL nicht verstanden