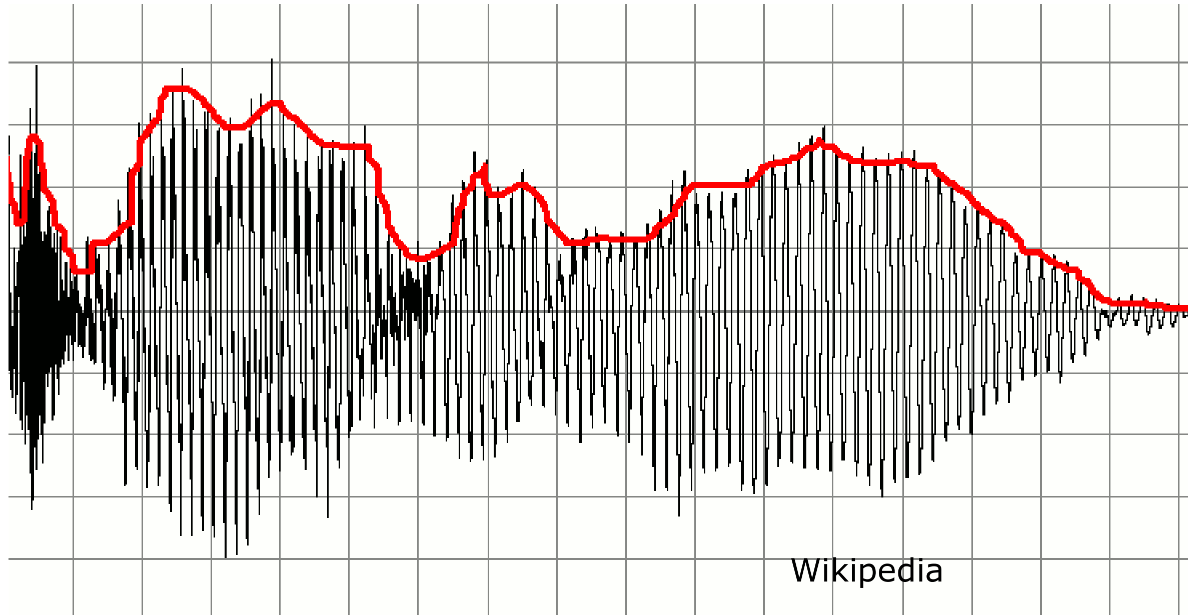
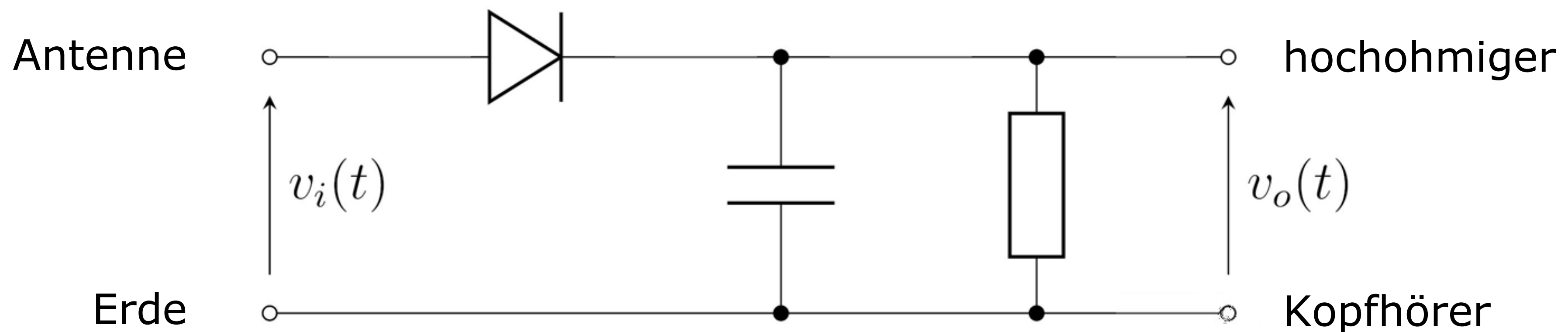
Hüllkurvendemodulator (oder H.detektor)

Demodulator für amplitudenmodulierte Signale (HF Trägers. + NF Nutzs.)

Gleichrichter + Tiefpass





Kristalldetektor

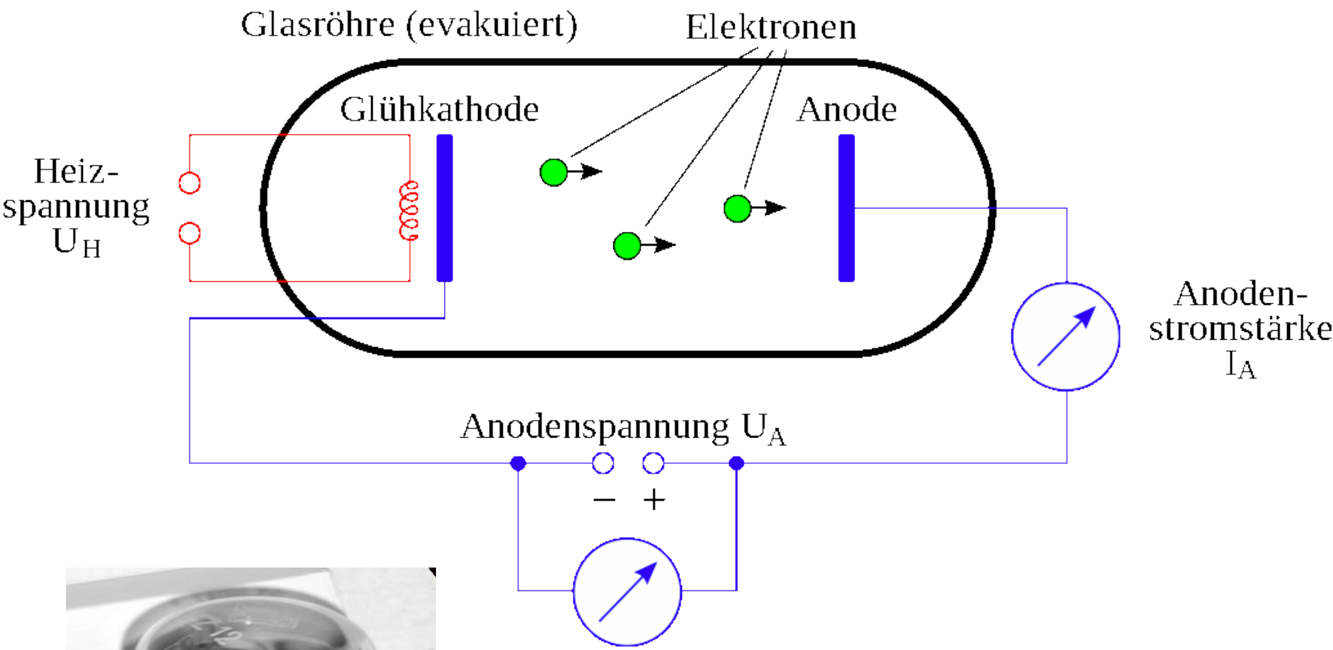
Schottkykontakt

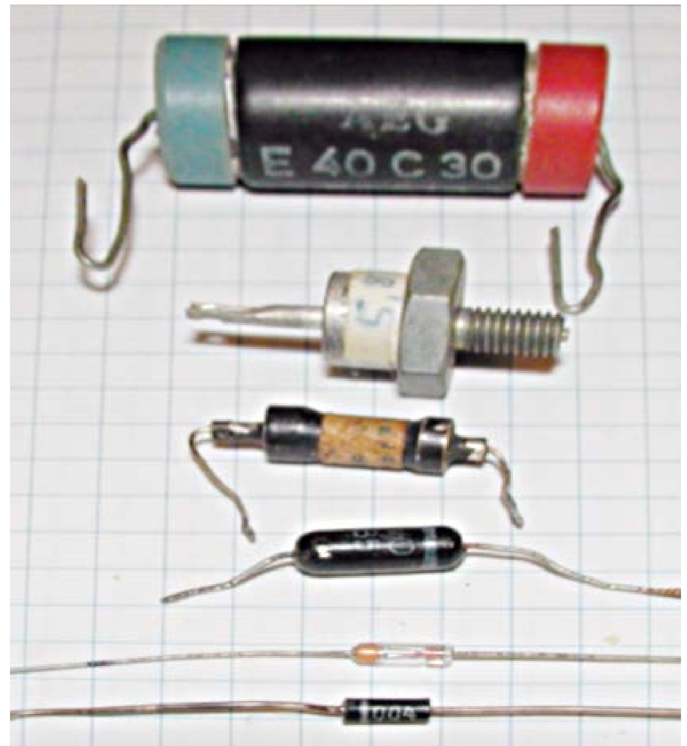
z.B. PbS (Bleiglanz)

+ Metallspitze

Röhrendiode

Halbleiterdiode





Halbleiterdiode

in IC

Beleuchtung: Glühfaden, Gasentladung, LED

Logikschaltungen: Relais, Röhren, Transistor, IC

Halbleiterbauelemente: Grenzflächen

HL-Vakuum, HL-Metall, HL-HL

Grenzfläche stört oben berechnetes Gleichgewicht von p, n

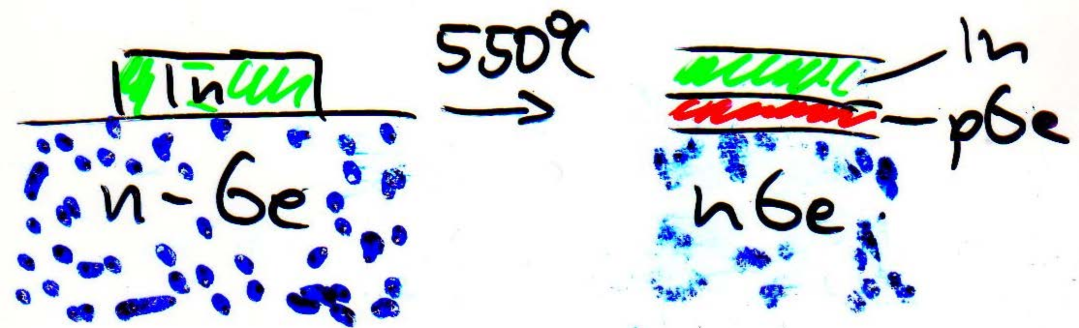
bewegliche Ladungen reagieren, Ionen sind aber ortsfest

$\Rightarrow$ Raumladungszonen

''1. Paradebeispiel'': *pn*-Übergang

Ziel: ρ(x), E(x), C(U)

Herstellungsverfahren: z. B. Diffusion, Implantation



"virtuelle" Herstellung:

Zusammenfügen je eines n- und p-Blocks

Gradient der e- und h-Dichten

Diffusionsströme j_D

e: n→p; h: p→n

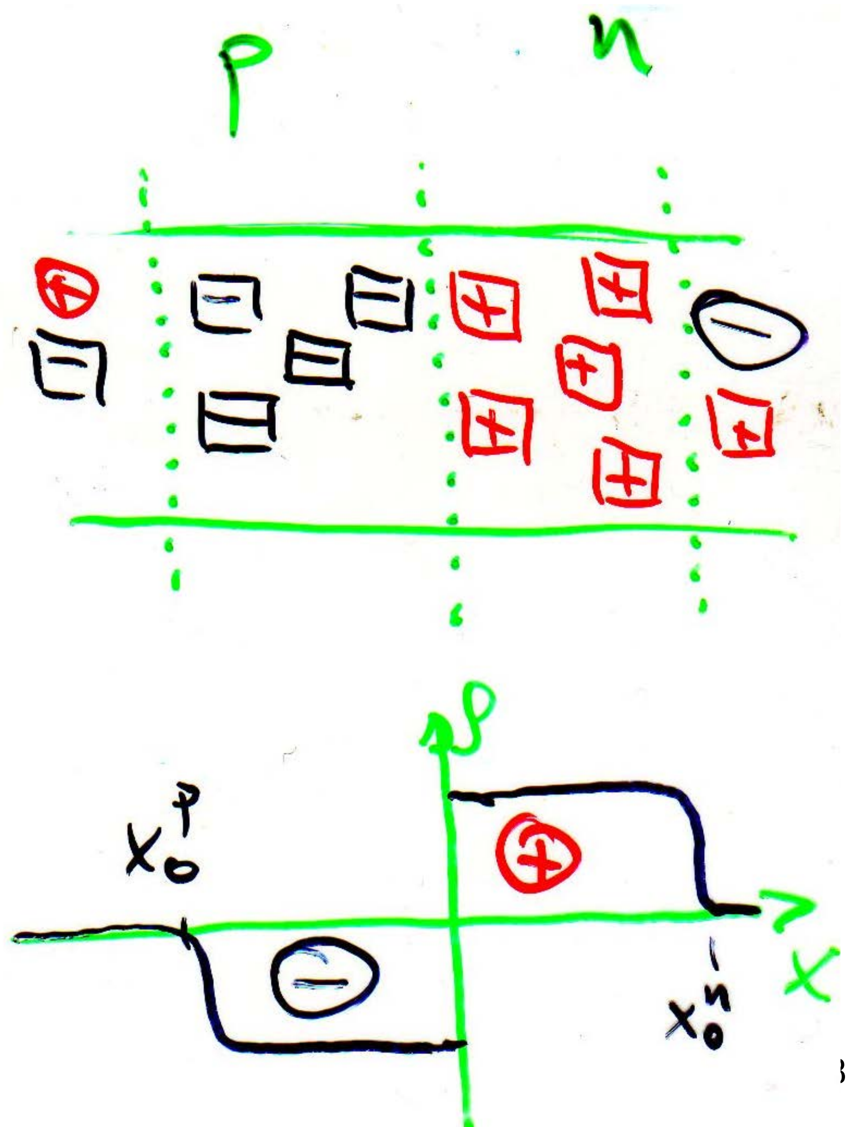
Ionen bleiben zurück

e & h rekombinieren

"steady state"

Raumladungszone

Verarmungszone

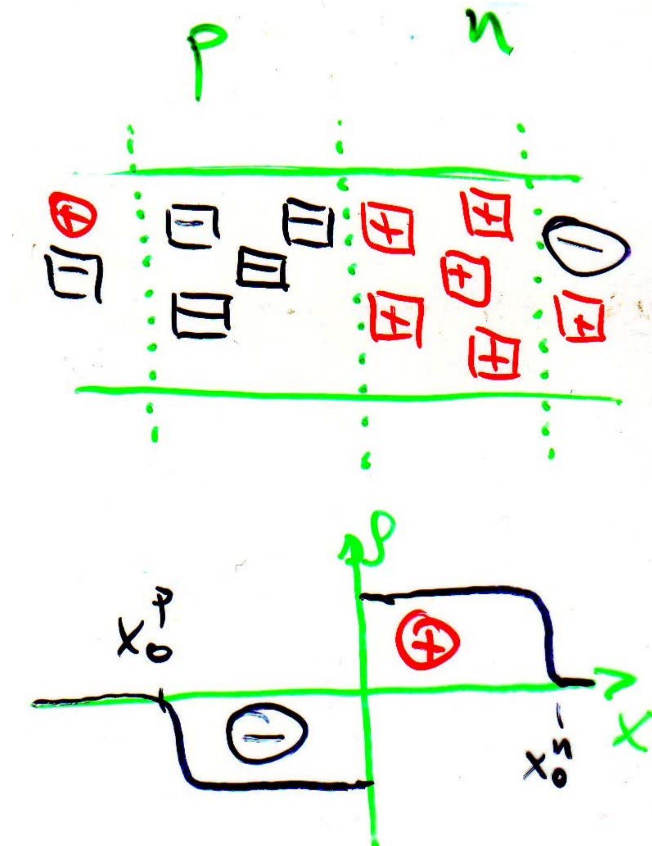


Raumladung → E-Feld → Feldstrom j_F

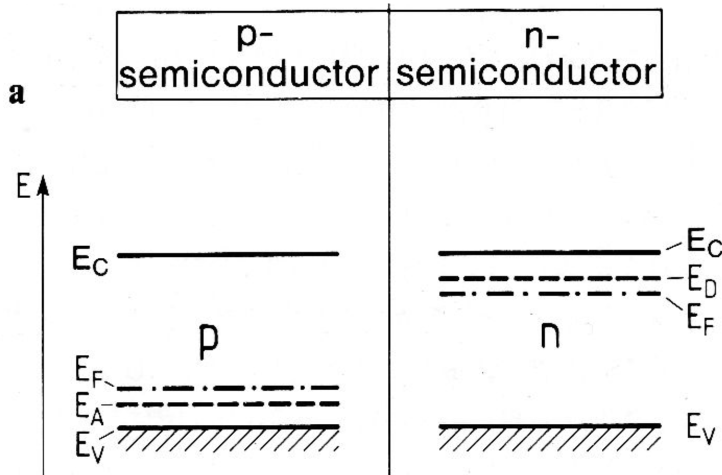
j_F ist entgegengesetzt zu j_D

→ dynamisches Gleichgewicht mit $j_D + j_F = 0$

dann ist $E_F(x) = \text{const.}$

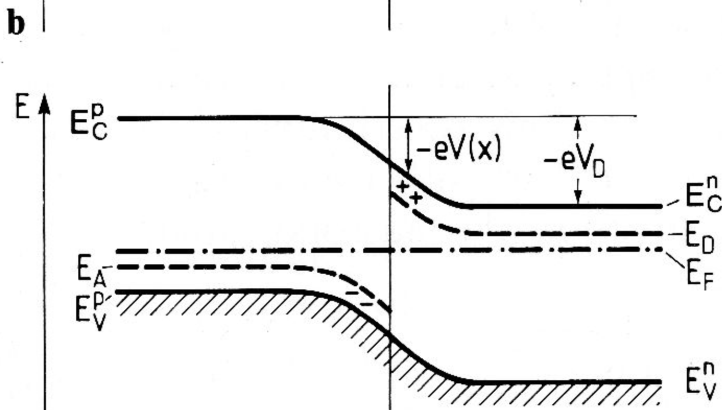


pn-Übergang



Vor Kontakt

- abrupt transition from p to n doping
- all dopants ionized in bulk semiconductors



Kontakt im Gleichgewicht

N_j densities, j = A)cceptors, D)onors

E_i ground state energies

E_F "Fermi level" μ

E_C^p, E_V^p, E_C^n, E_V^n conduction/valence band edges deep in p/n regions

V_D diffusion voltage

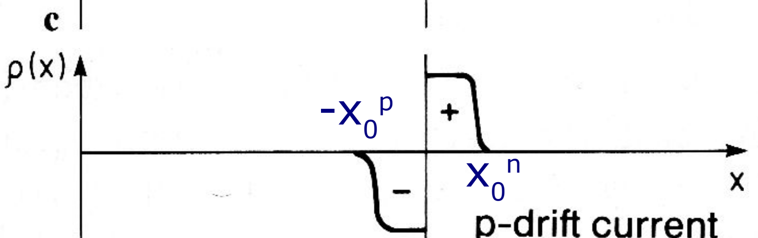
V(x) macropotential of p-n junction

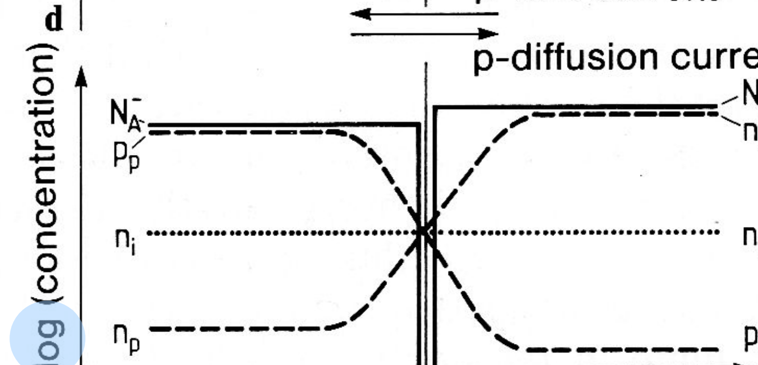
ρ(x) space charge density (ionized A, D)

n_i intrinsic electron concentration

$n_{n/p}$ electron concentrations on n/p side

$p_{n/p}$ hole concentrations on n/p side





E_F konstant ⇒ Bandverbiegung & Diffusionsspannung

Schottkymodell

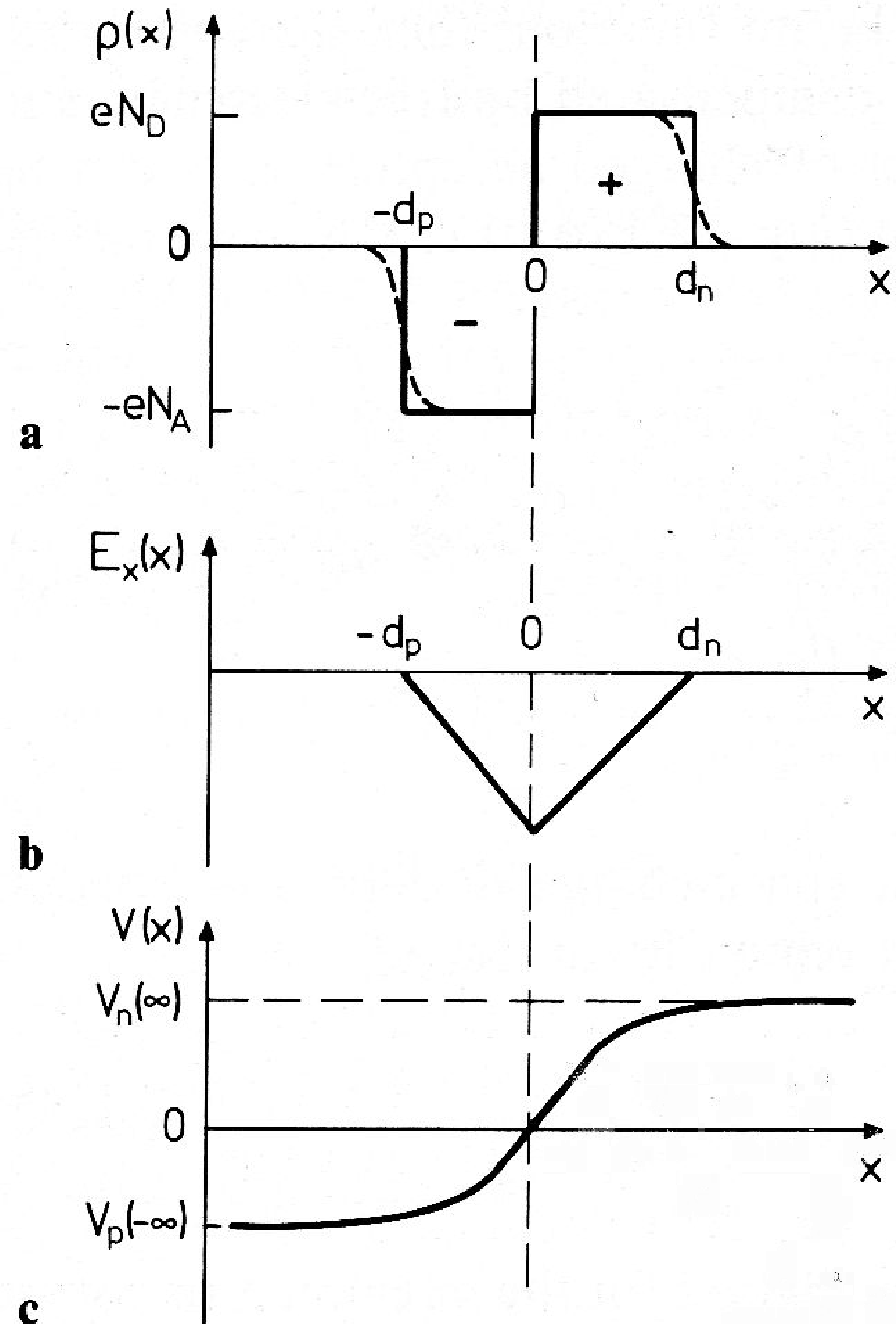


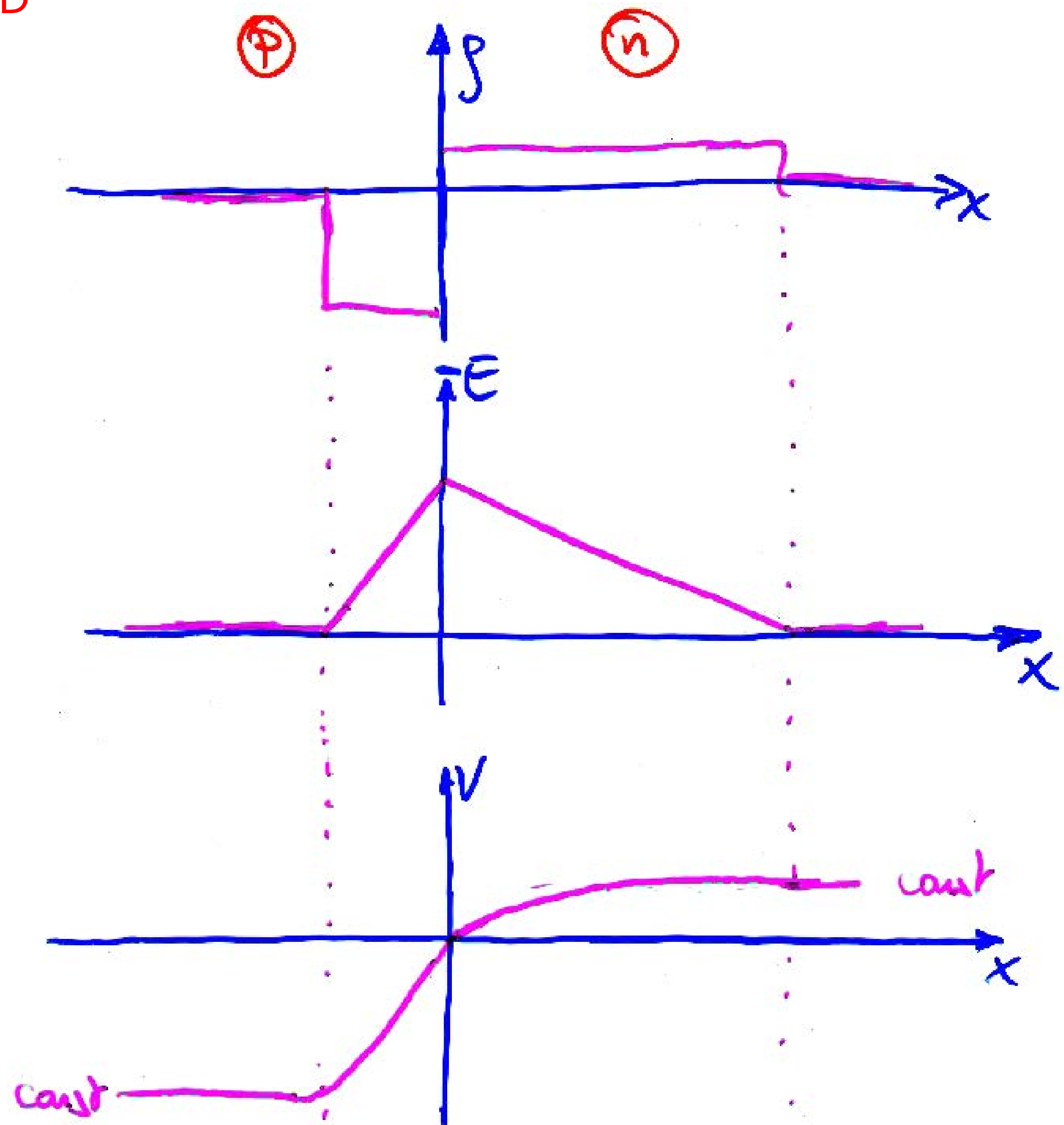
Fig. 12.16 a – c. The Schottky model for the space-charge zone of a $p-n$ junction (at $x=0$). **a** Spatial variation of the space-charge density $\varrho(x)$ produced by the ionized acceptors (N_A) and donors (N_D). The real form of the curve (*dashed*) is approximated by the rectangular (*full line*) form; **b** behavior of the electric field strength $E_x(x)$; **c** the potential $V(x)$ in the region of the $p-n$ junction

Schottkymodell

$$d^{(n)} = \frac{N_A}{N_D} d^{(p)} = \sqrt{2 \frac{\epsilon \epsilon_0}{e} (V_D - U) \frac{N_A}{N_D} \frac{1}{N_A + N_D}}$$

$$E(0) = 2 \frac{V_D - U}{d^{(n)} + d^{(p)}}$$

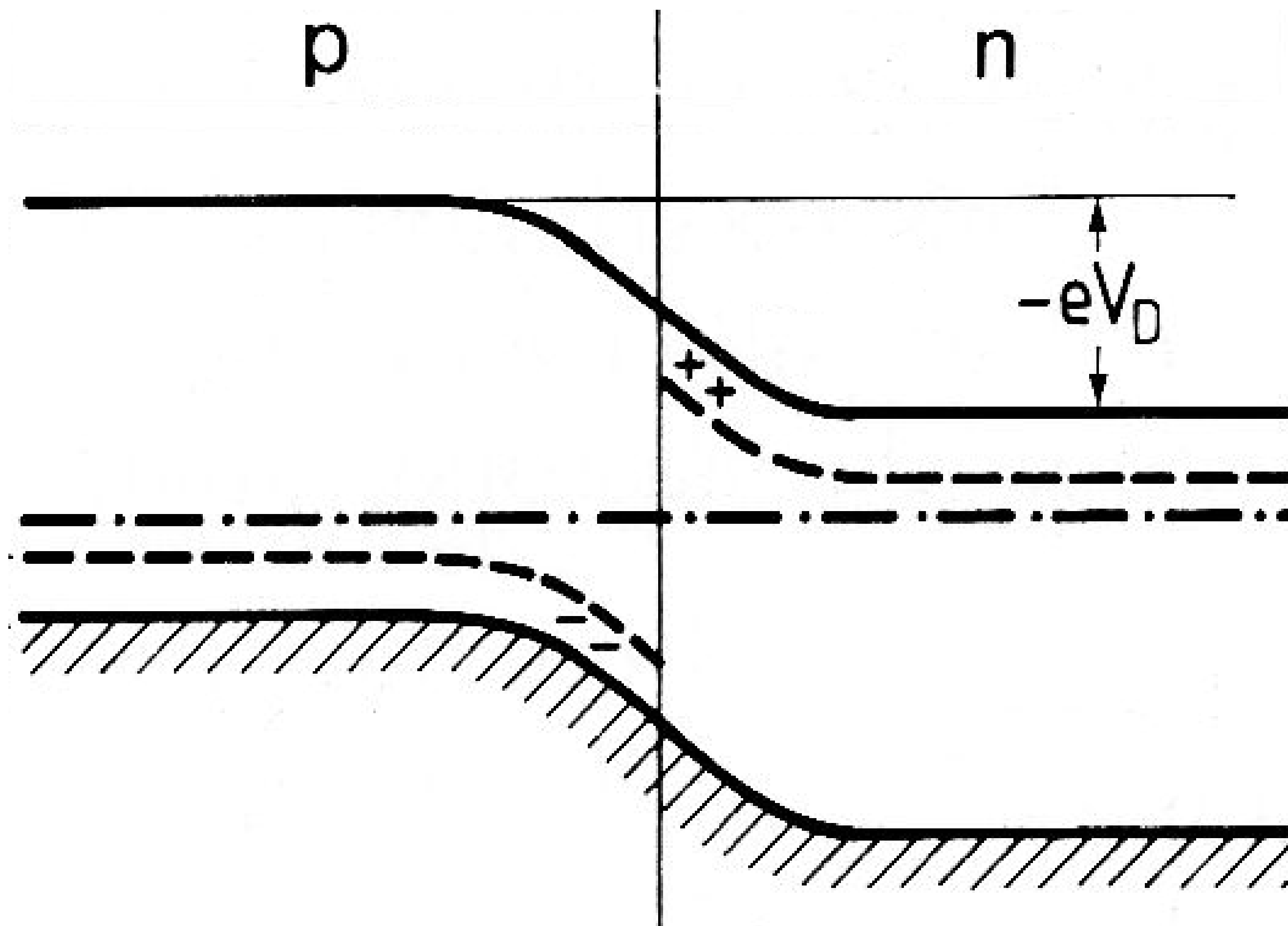
Resultat für $N_A \gg N_D$



Weitere Steigerung von N_A:

Metall-Halbleiter-Kontakt

Schottky-Diode


p
n
$-eV_D$
+ +
− −

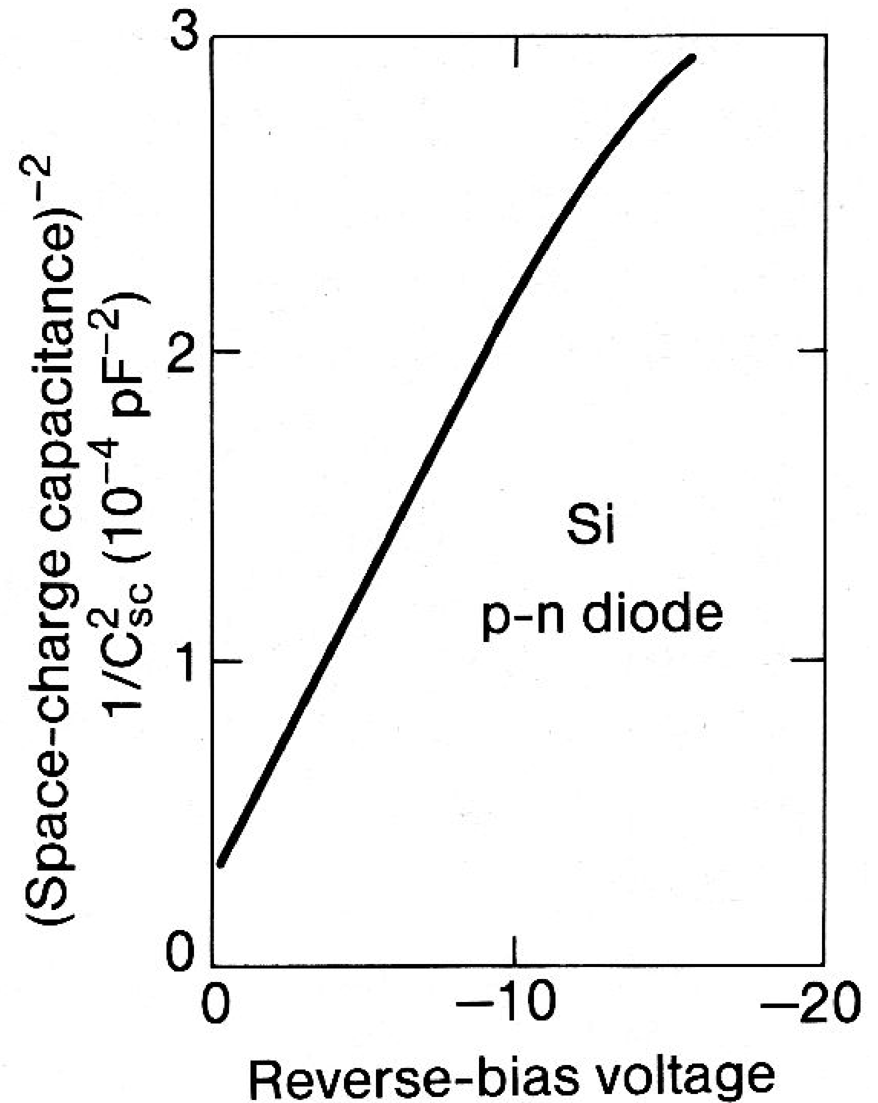
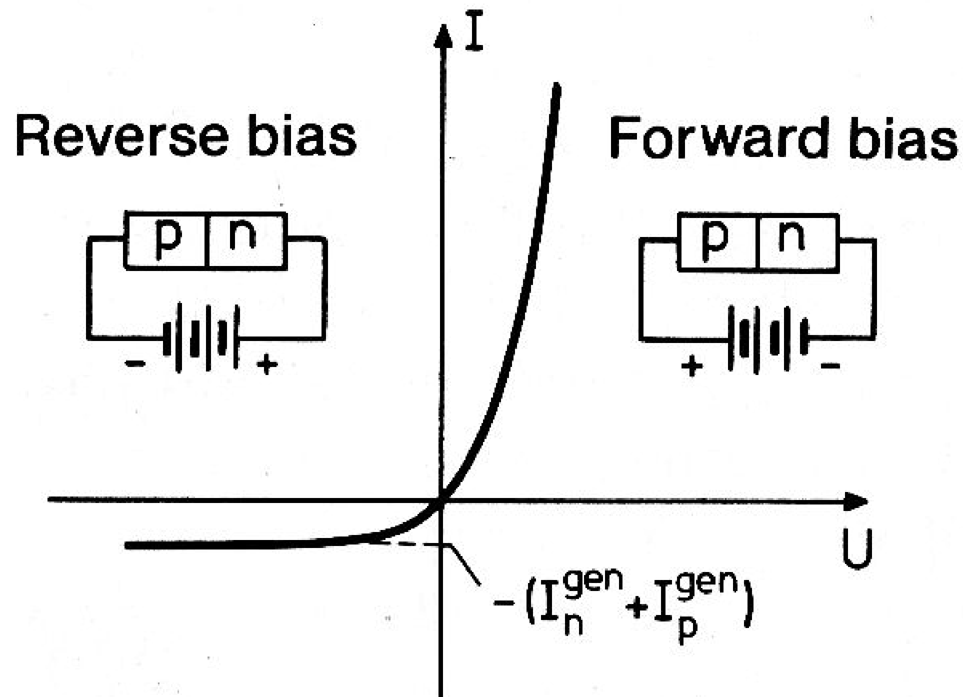


Fig. 12.20. Experimentally determined relationship between the space-charge capacitance and the reverse voltage (indicated by negative values) for the Si $p-n$ diode discussed in Fig. 12.19. (From the advanced lab. course of the II. Physics Institute of the RWTH Aachen)

Rectification at a pn-Junction



Schematic current-voltage characteristics

Maximum reverse current:

Fig. 12.17 Ibach-Lüth

sum of electron and hole generation currents

Experimental I-V characteristics of a Si p-n junction

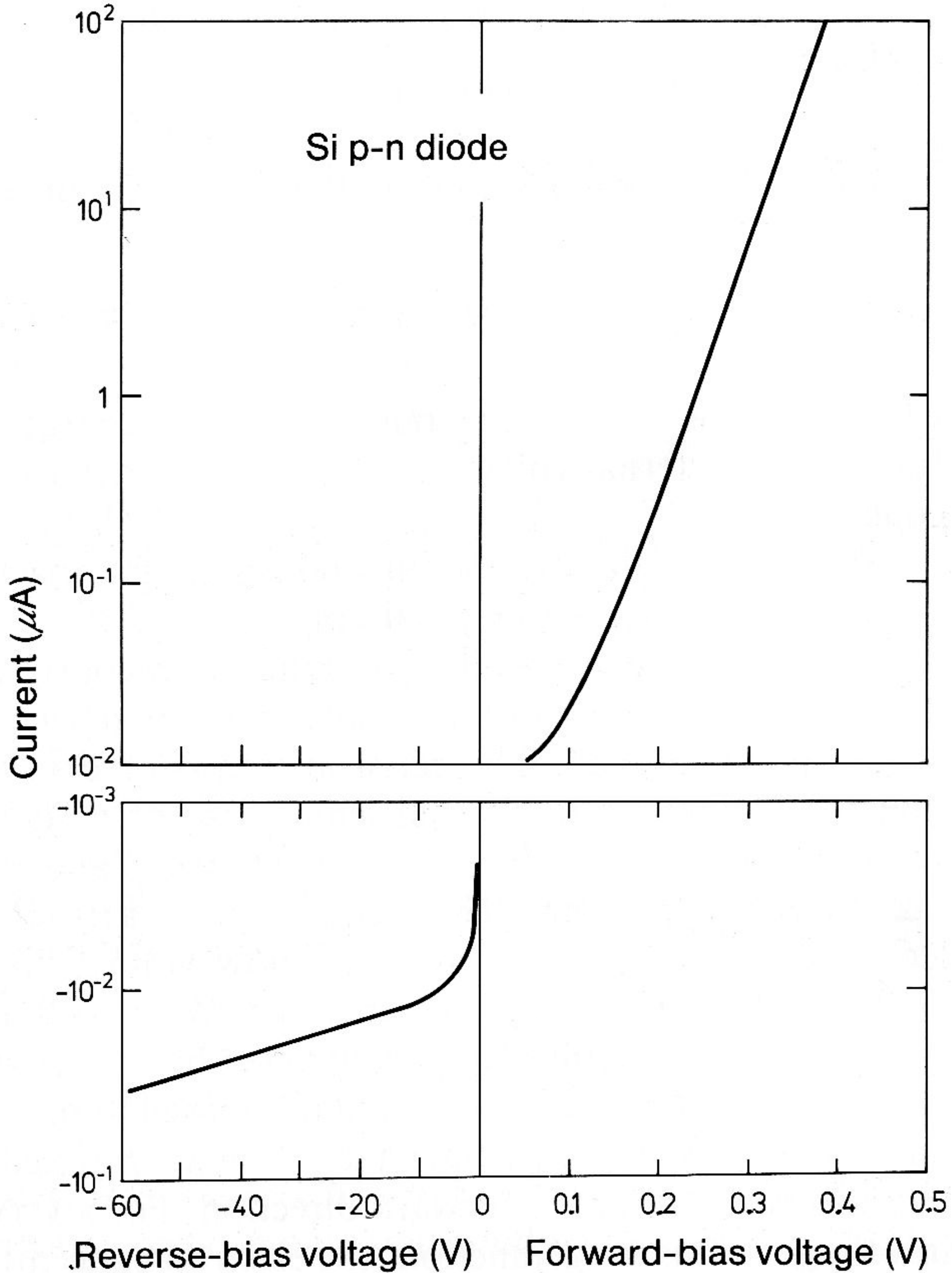
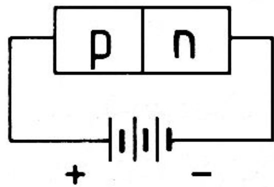


Fig. 12.19 Ibach-Lüth

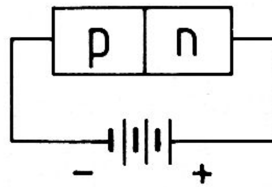
Lab course
II. Physikalisches Institut
RWTH Aachen

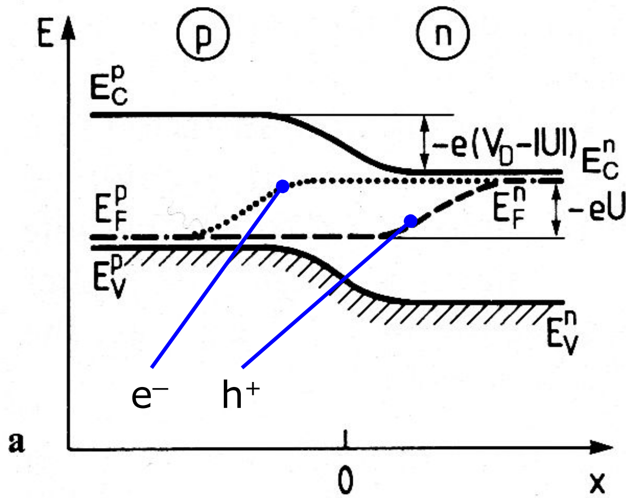
Non-equilibrium situation: Quasi Fermi levels

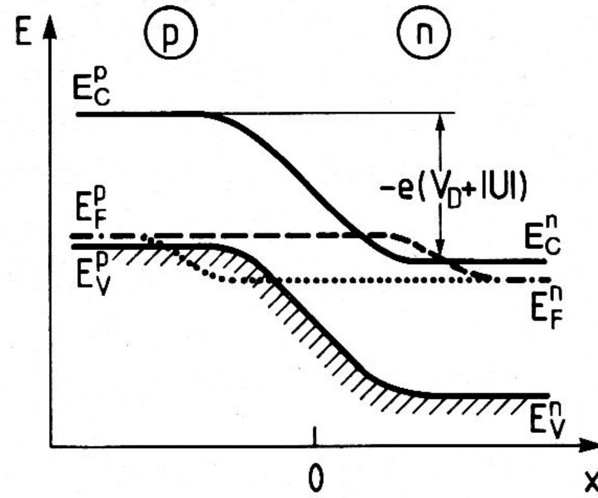
Forward bias

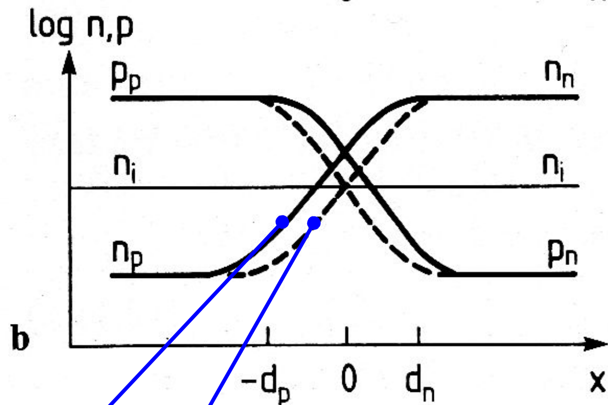


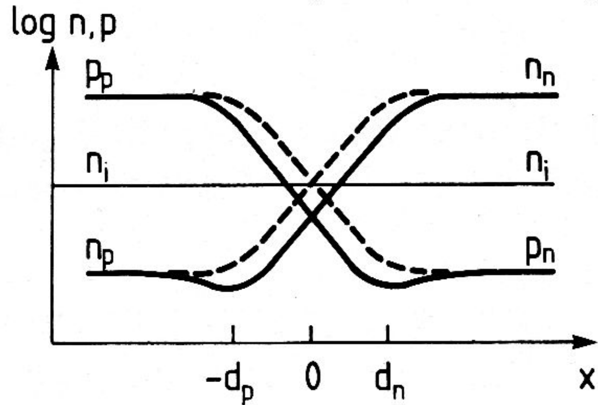
Reverse bias











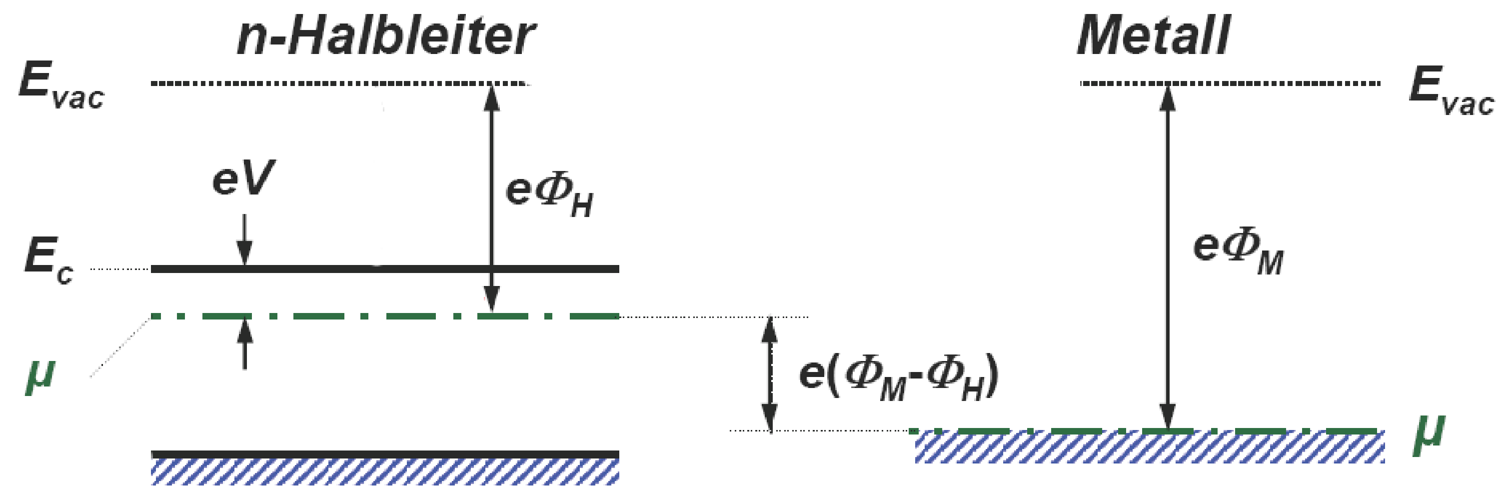
Bias No bias

Fig. 12.18 a, b. Forward- and reverse-biased $p-n$ junctions (non-equilibrium state). **a** Band scheme in the presence of an external voltage $+U$ or $-U$. The Fermi levels E_F^p and E_F^n in the p and n regions are shifted with respect to one another by eU. In the region of the $p-n$ junction, the equilibrium Fermi level $(-\cdot-)$ splits into so-called quasi Fermi levels for electrons $(\cdots)$ and for holes $(---)$; **b** spatial variation of the concentration of holes p and electrons n in a biased $p-n$ junction (*full line*) and without bias at thermal equilibrium $(---)$. The lengths $-d_p$ and d_n give the range of the space charge zone in thermal equilibrium, i.e. without bias voltage. The carrier concentrations deep in the p and n regions are denoted p_p, n_p and p_n, n_n, respectively

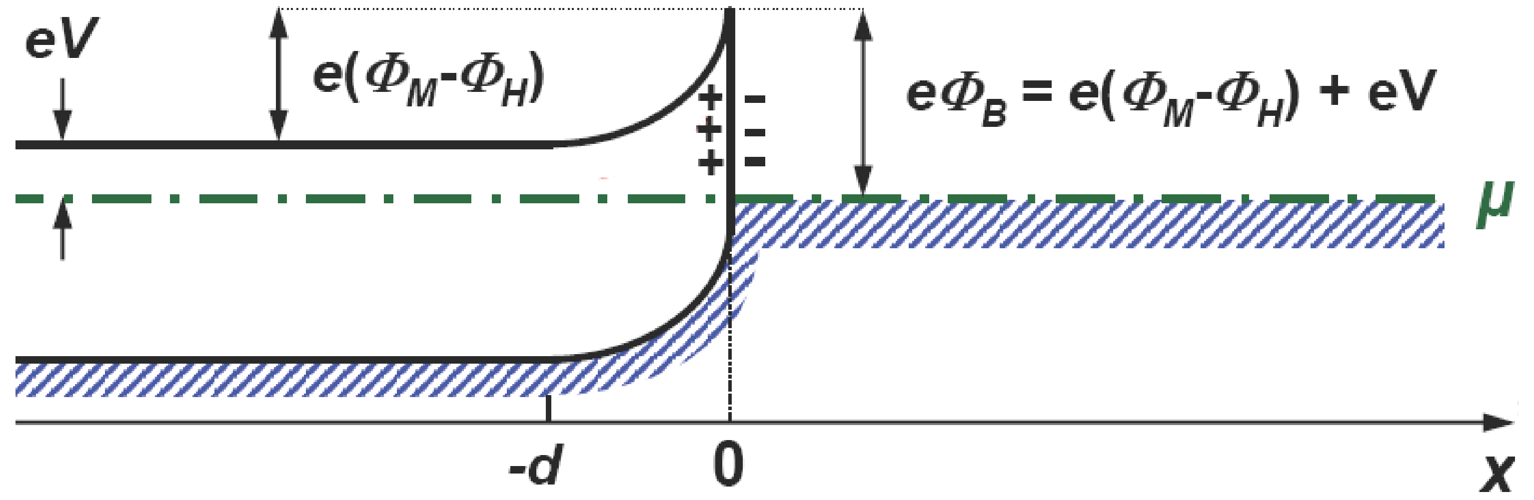
Ohne Drähte geht's nicht: Schottky-Kontakt

getrennt

V: ext. Spannung



Kontakt



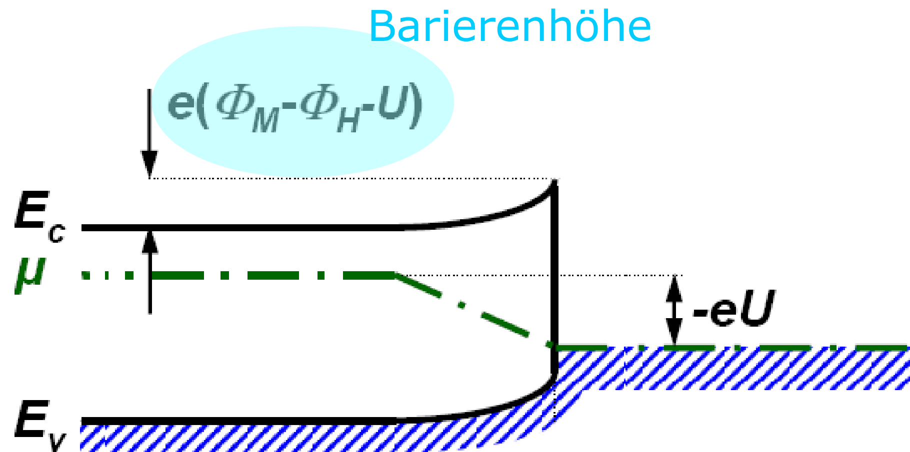
Kontaktpotential: $e\,V_K = \Phi_M - \Phi_H$

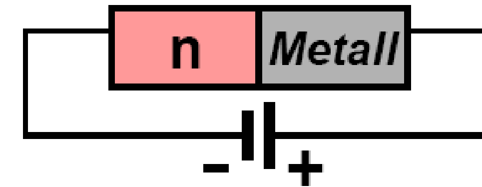
Rechnung wie pn-Übergang: $V(x) = -(e\,N_D) / (2\varepsilon\varepsilon_0)\,(d - x)^2$

$V(0) = V_K + V$ also $d(U=0) = \left((2\varepsilon\varepsilon_0)/(e\,N_D)\,V_K \right)^{1/2}$

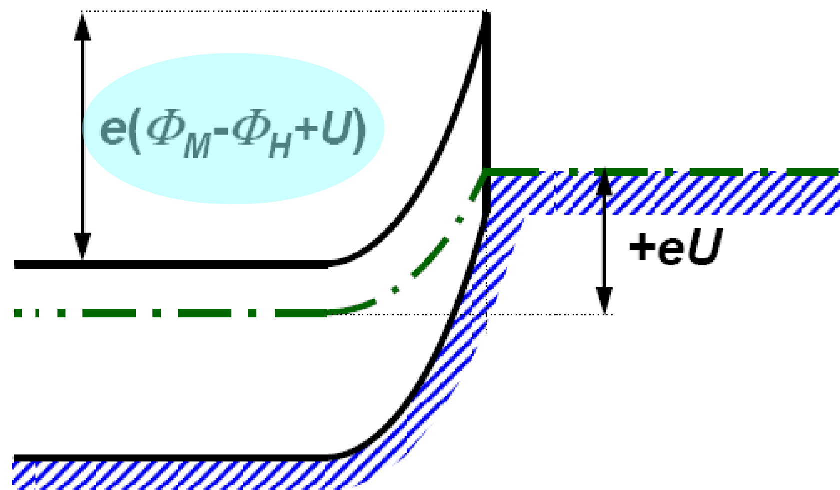
Schottkydiode (im Schottkymodell)

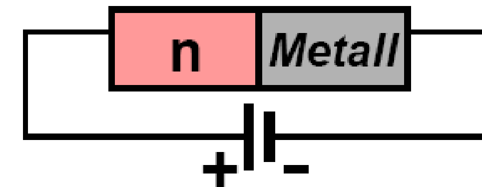
Barierenhöhe





Durchlassrichtung





Sperrrichtung

Ohmsch bei großem N_D (Tunneln)

Abweichungen vom Shockley-Modell

Zuleitungswiderstände

Oberflächenkanäle

Erzeugung/Vernichtung

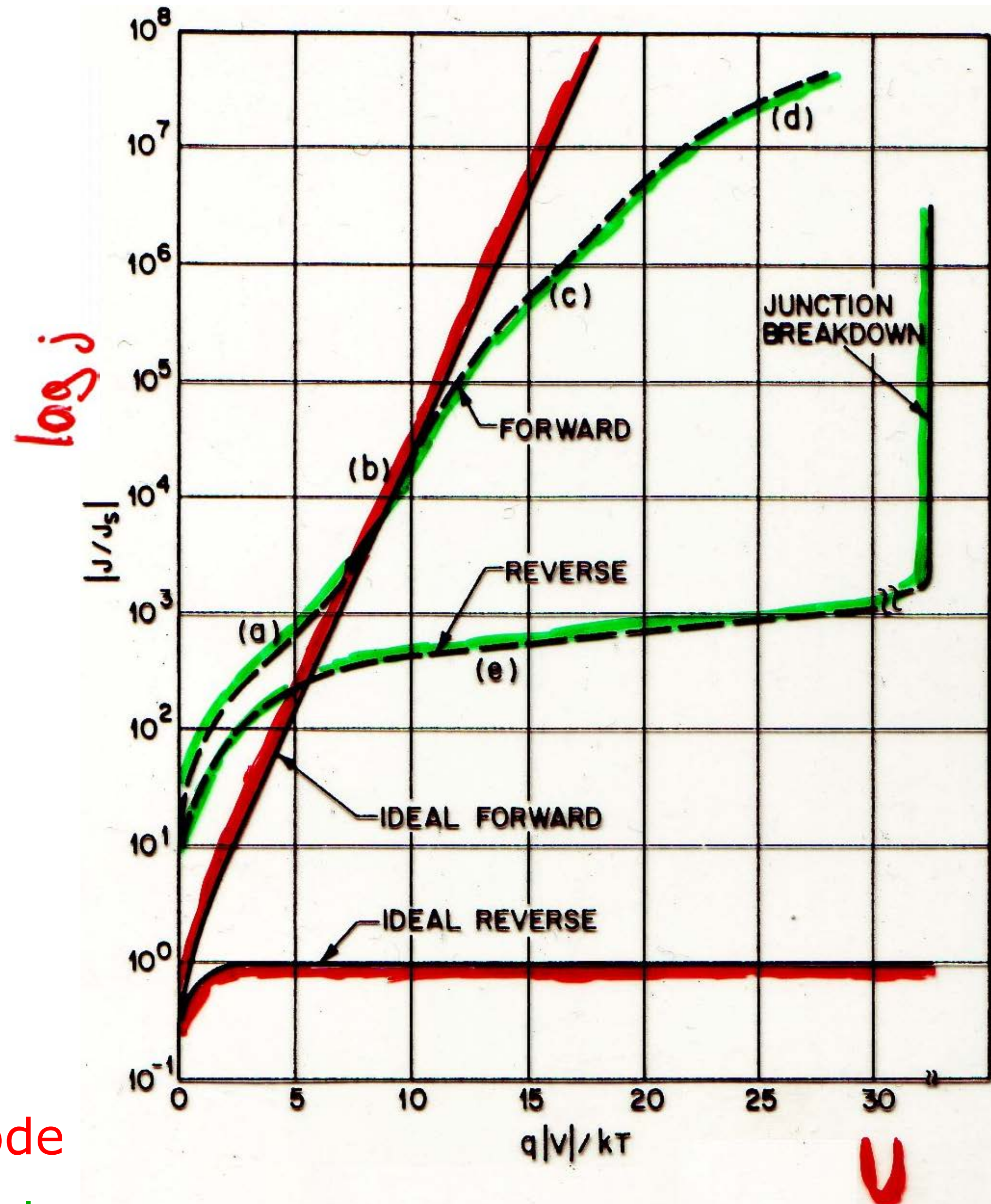
in Verarmungszone

Tunneln

starke Injektion

(i. e. Dichte von eindiffundierenden

e^- im p-Bereich mit n vergleichbar)



Shockley-Diode

reale Si-Diode

Zener-Diode

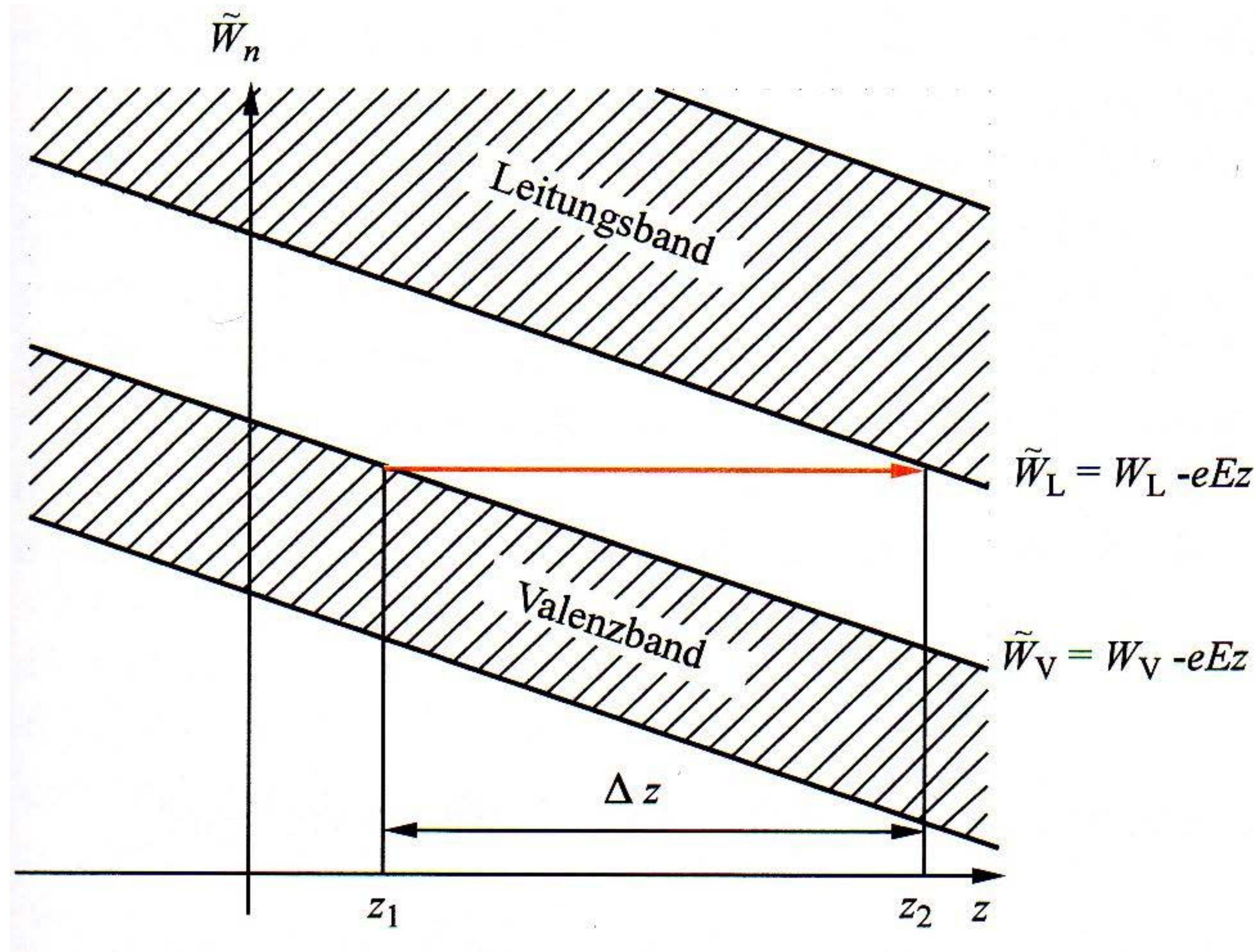


Abb. 8.19
Zum Zener-Effekt

Bei hoher Sperrspannung:

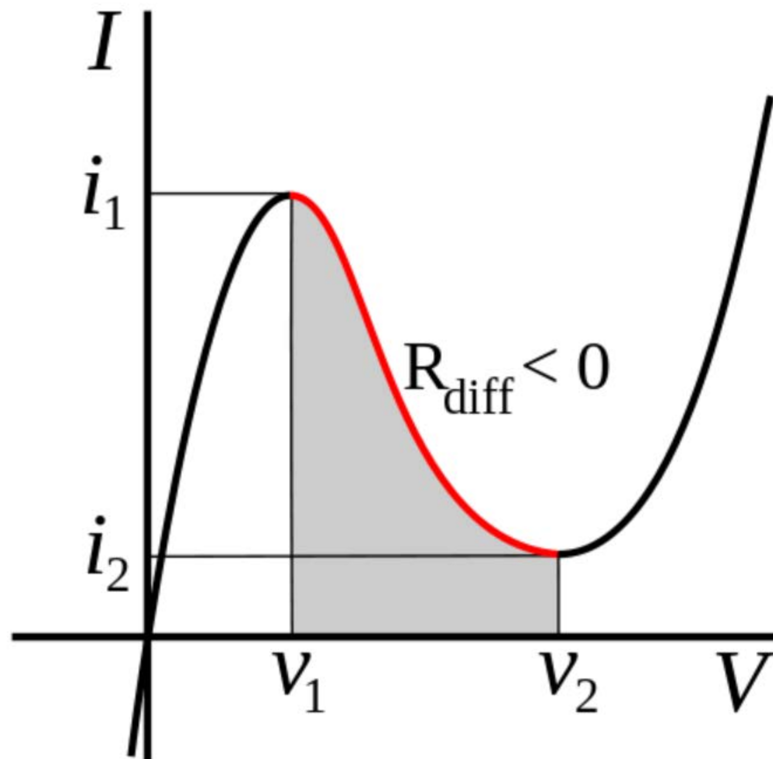
Tunneln durch Verarmungszone.

⇒ rapider Anstieg des Sperrstroms

Esaki- oder Tunneldiode

erfunden 1957 bei Tokyo Tsushin Kogyo (heute Sony)

NDR: parallel zu Schwingkreis werden Verluste (R) kompensiert



Leo Esaki (* 1925)

Nobelpreis Physik 1973

GENERAL ELECTRIC

Research Laboratory

TUNNEL DIODES

Published by

Research Information Services

November 1959

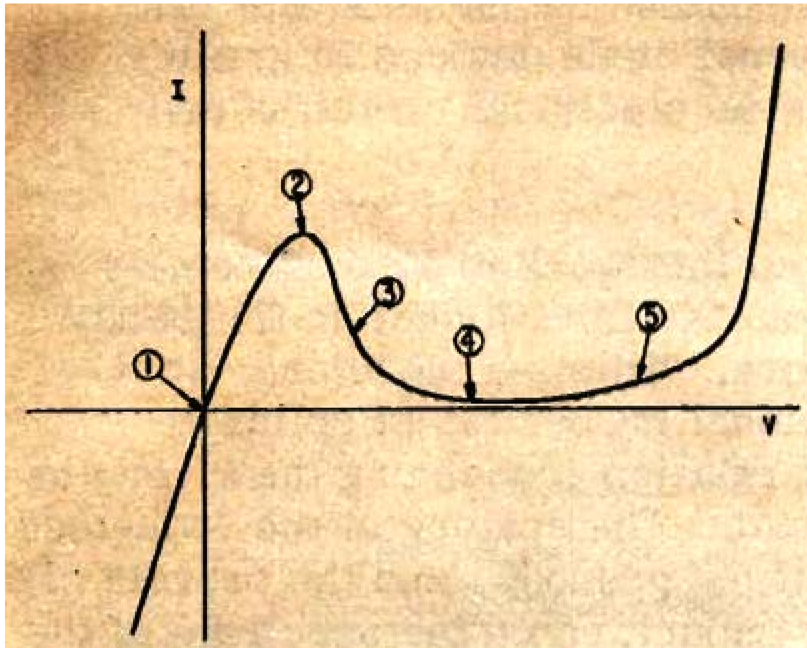


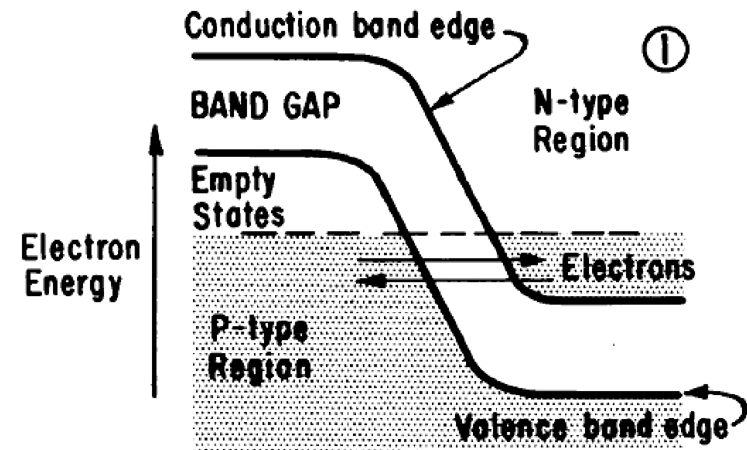
FIGURE 2

CURRENT-VOLTAGE CURVE

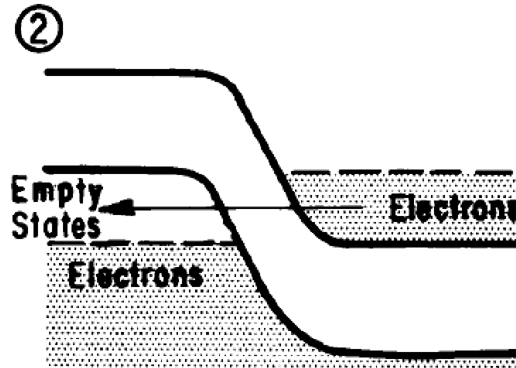
FIGURE 1

TUNNEL DIODE JUNCTION
AT VARIOUS BIAS CONDITIONS

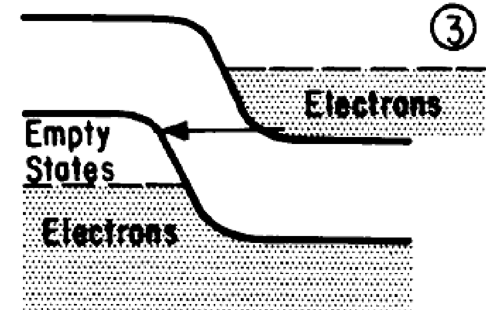
(The numbered diagrams below correspond to the numbered points on the current-voltage curve, Figure 2.)



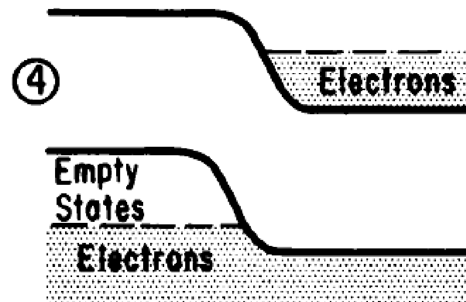
Electrons at same level on both sides of junction. No net current.



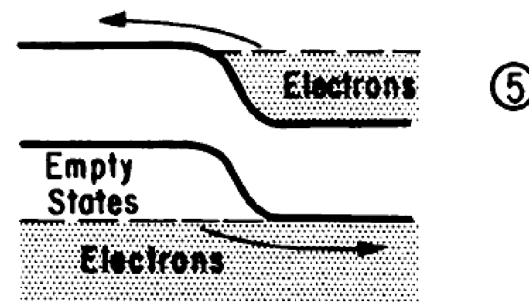
Electrons on right side are raised until they are opposite empty states on left side. Strong current flows from right to left.



Electrons on right raised still farther. Some are opposite "forbidden band gap," some opposite empty states. Current decreases.

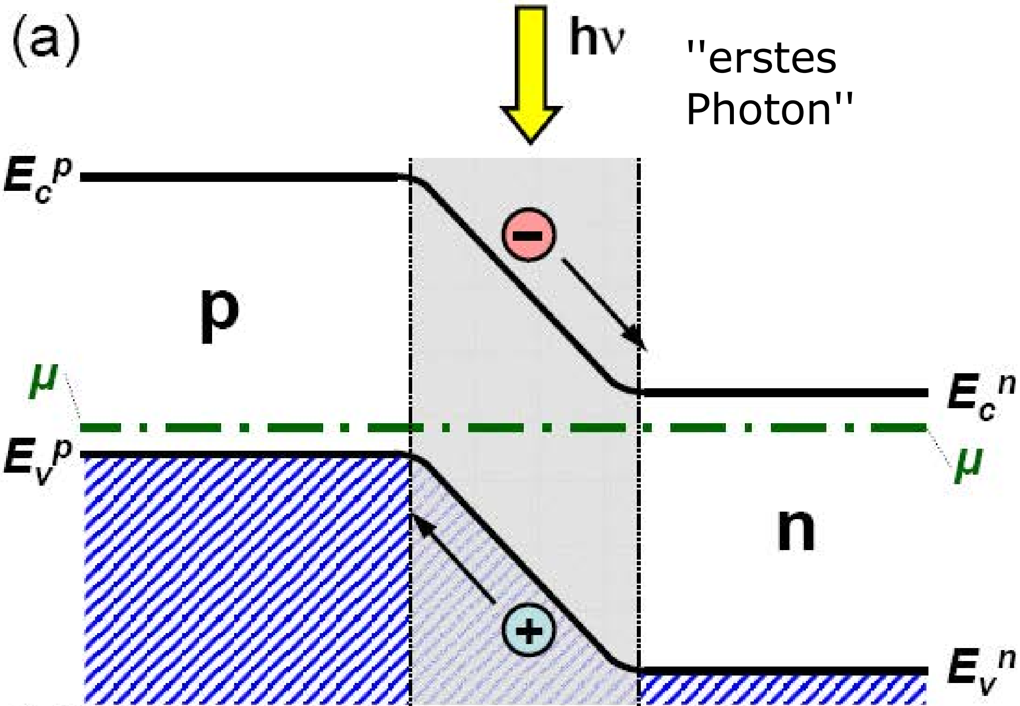


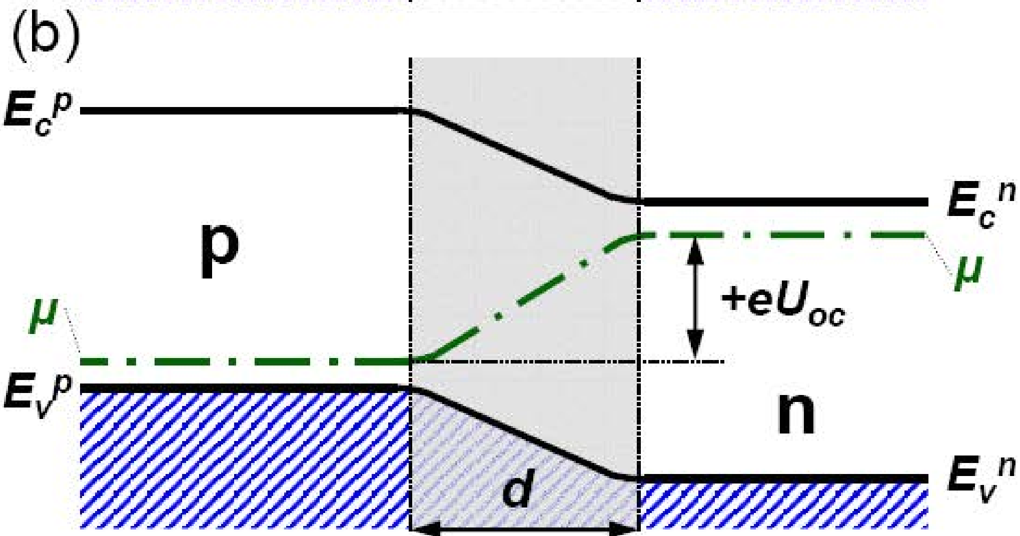
Electrons all are opposite forbidden gap. Very small current.

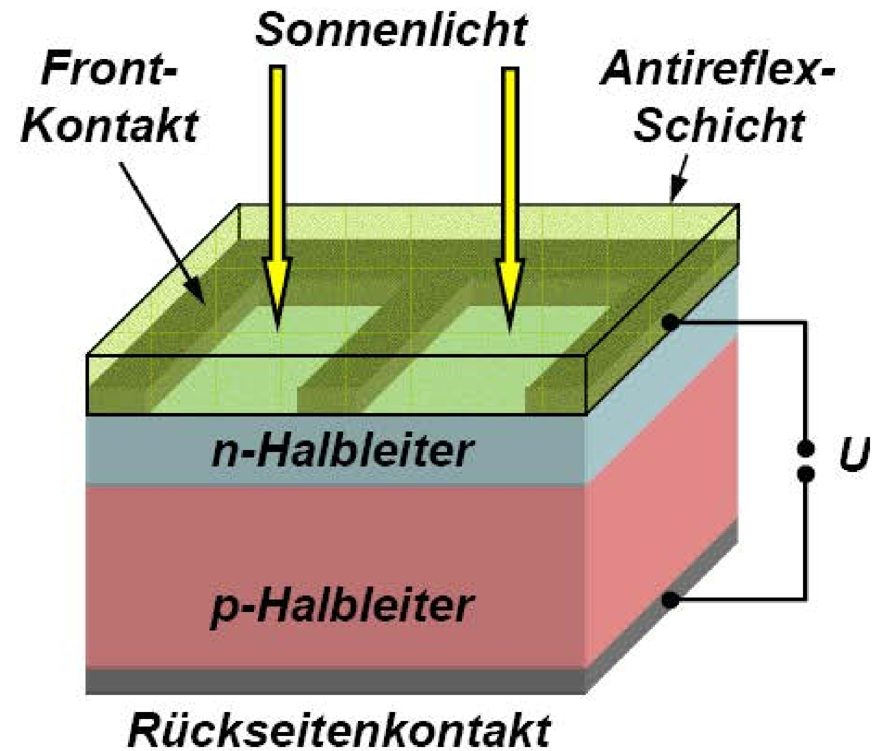


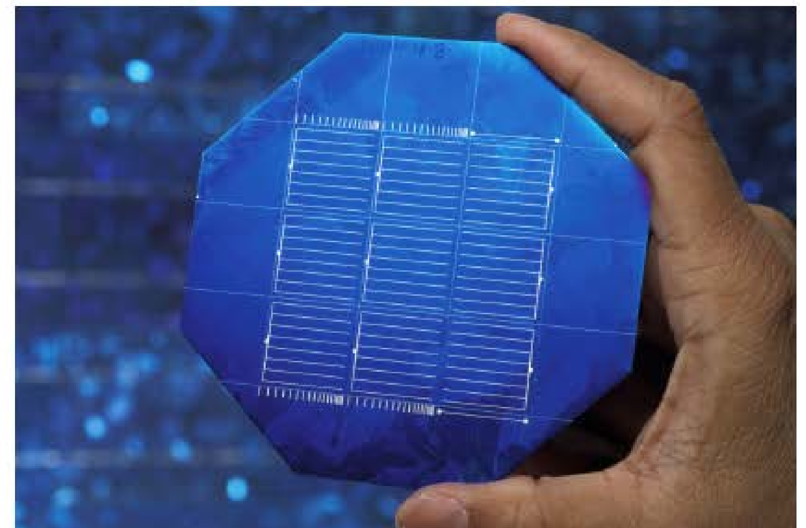
Electrons raised until they spill over barrier. Current increases.

Solarzelle









viel Licht: Spannung U_{oc} (open circuit)

Material	Struktur	Wirkungsgrad (%)	
		Labor	Produktion
Si	amorph	13	5–7
	polykristallin	18	13 – 15
	einkristallin	24	14 – 17
GaAs	Einschicht	25	15 – 22
	Mehrschicht	32	20 – 28

Preis, Giftigkeit

Details zu Widerstand des Materials, Verlust bei E_{photon} größer als E_g

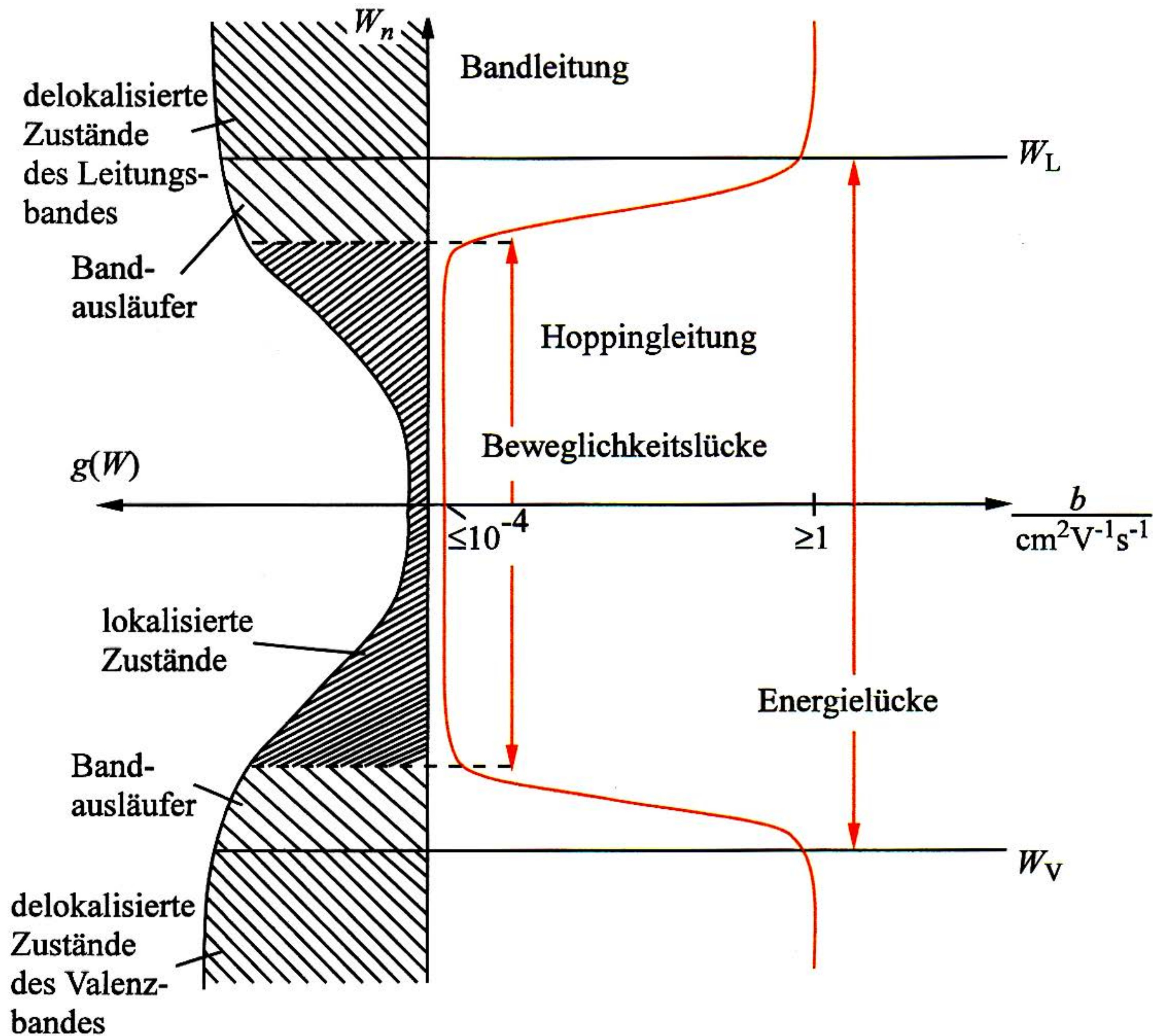


Abb. 7.22

Energiezustände W_n, Zustandsdichte $g(W)$ und Beweglichkeit b für einen Isolierstoff