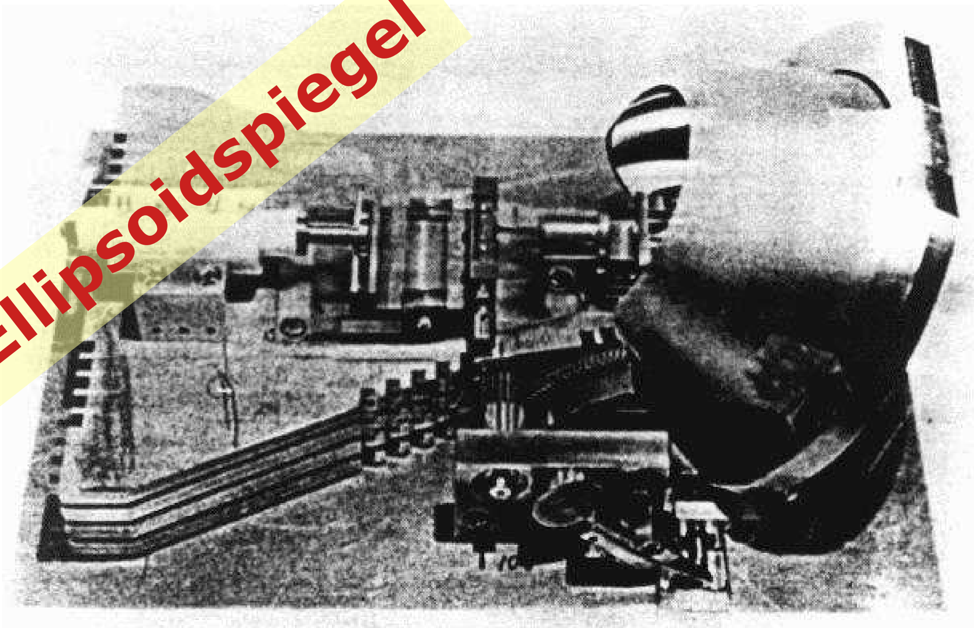
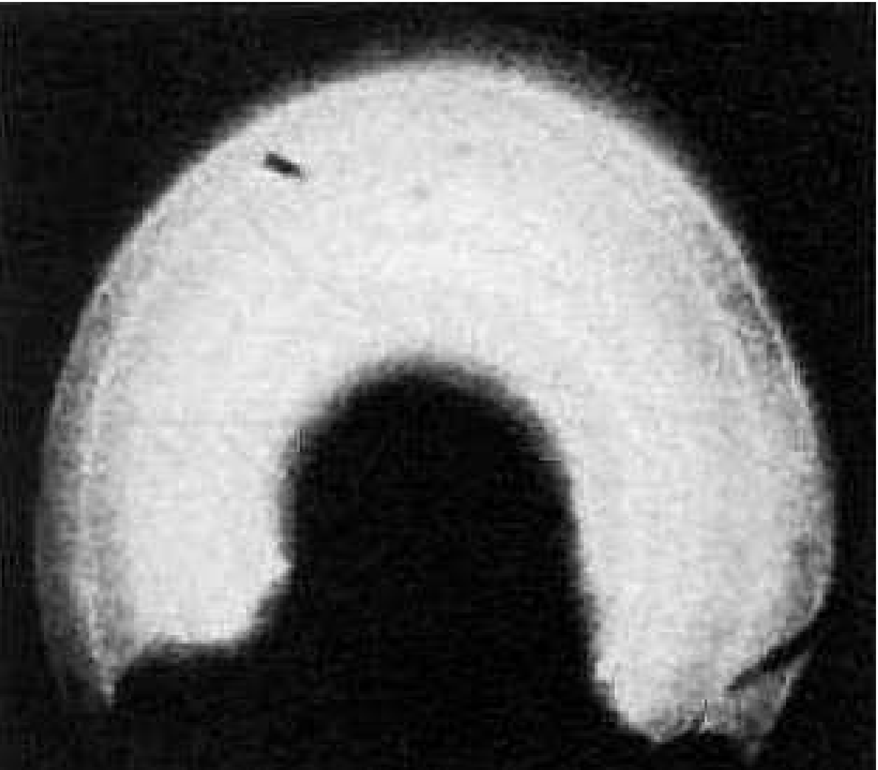
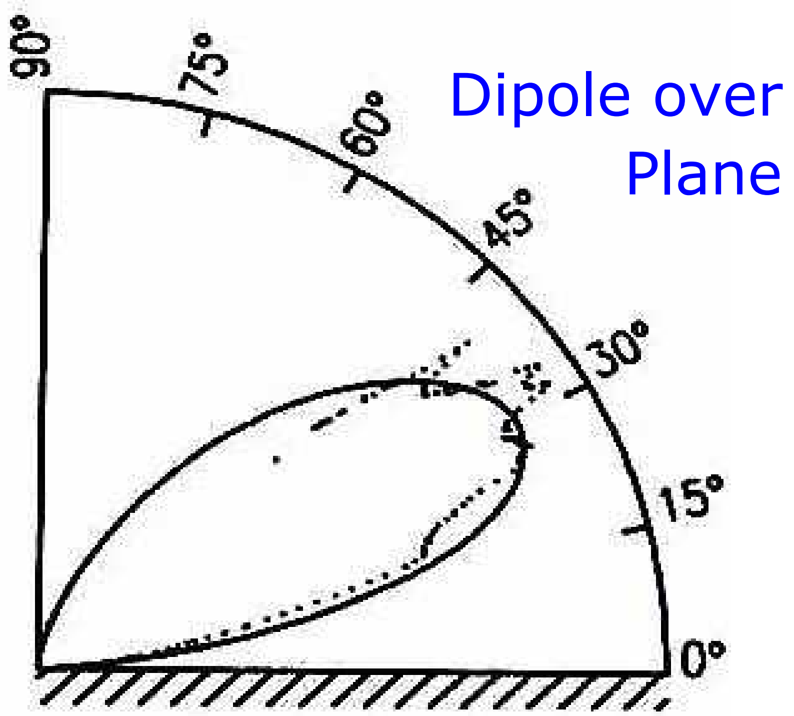


No Sun Glasses needed

J. Vac. Sci. Technol. B **9**, 897 (1991)

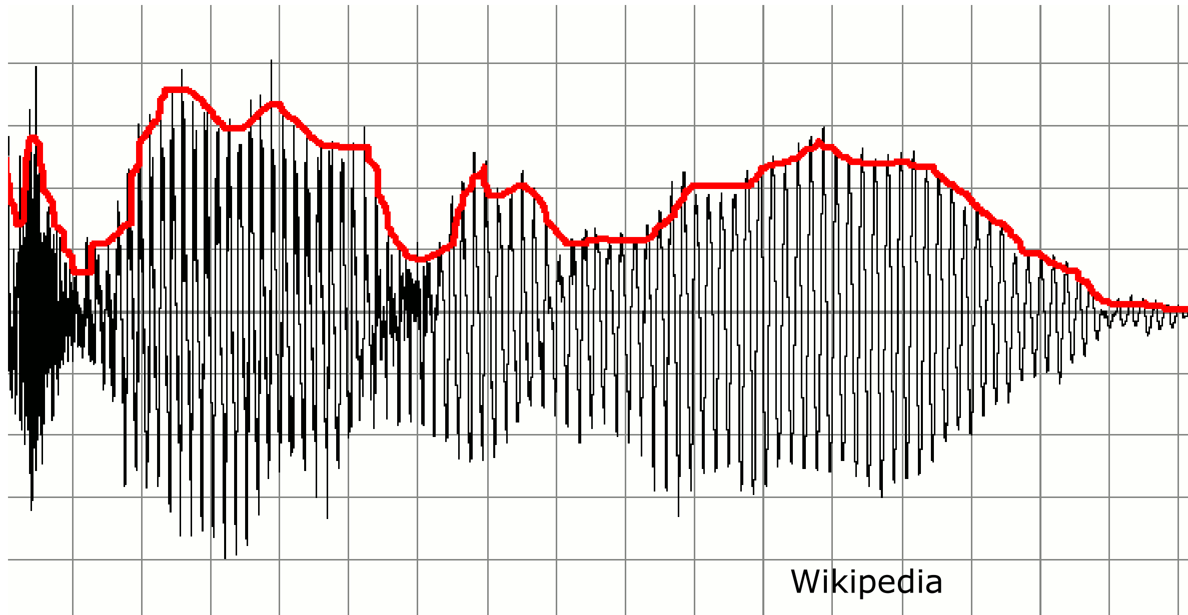


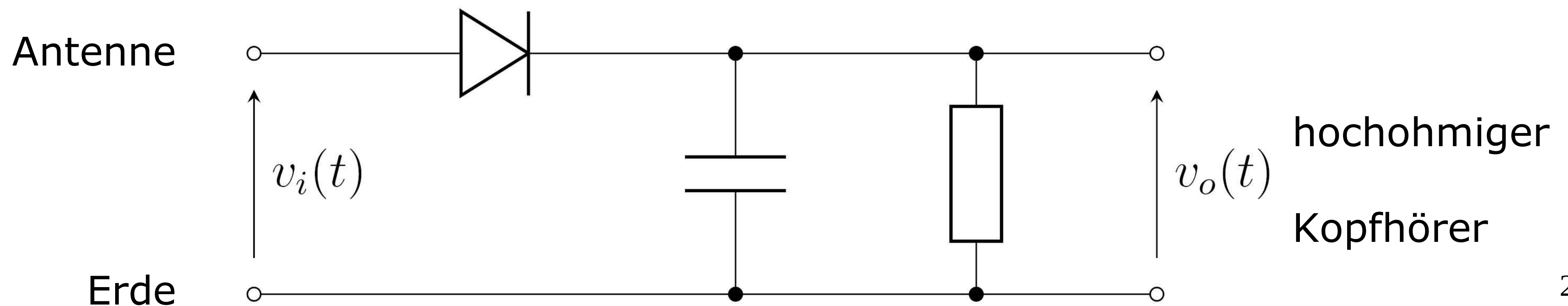


Hüllkurvendemodulator (oder -detektor)

demoduliert amplitudenmoduliertes Signal (HF Träger + NF Nutzsignal)

Gleichrichter + Tiefpass





Kristalldetektor

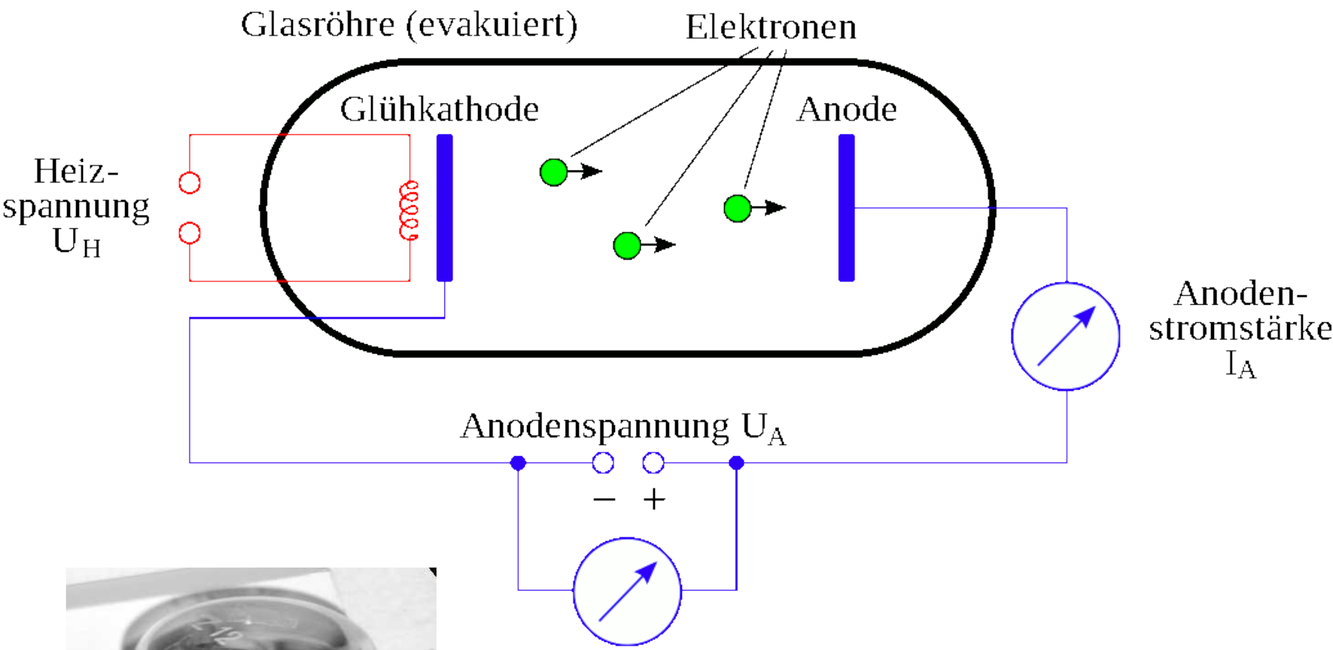
Schottkykontakt (Metall-HL)

z.B. PbS (Bleiglanz)

+ Metallspitze

Röhrendiode

Halbleiterdiode



Apple A12 Bionic, 2018:

(110 nm)² / Transistor

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

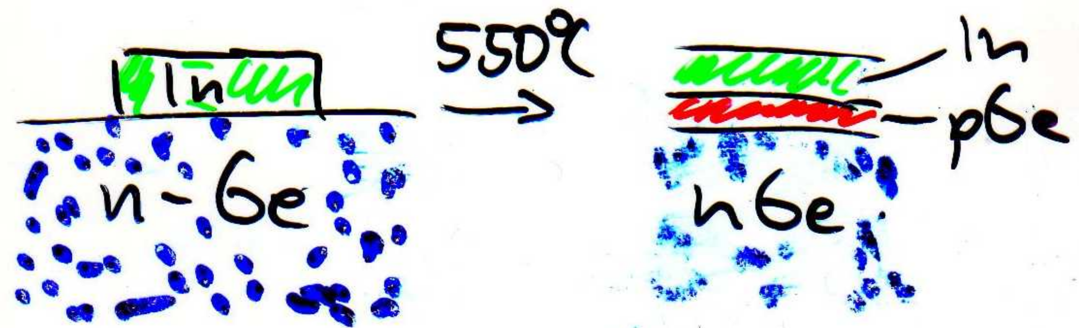
bewegliche Ladungen reagieren, Ionen sind aber ortsfest

$\Rightarrow$ Raumladungszonen

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

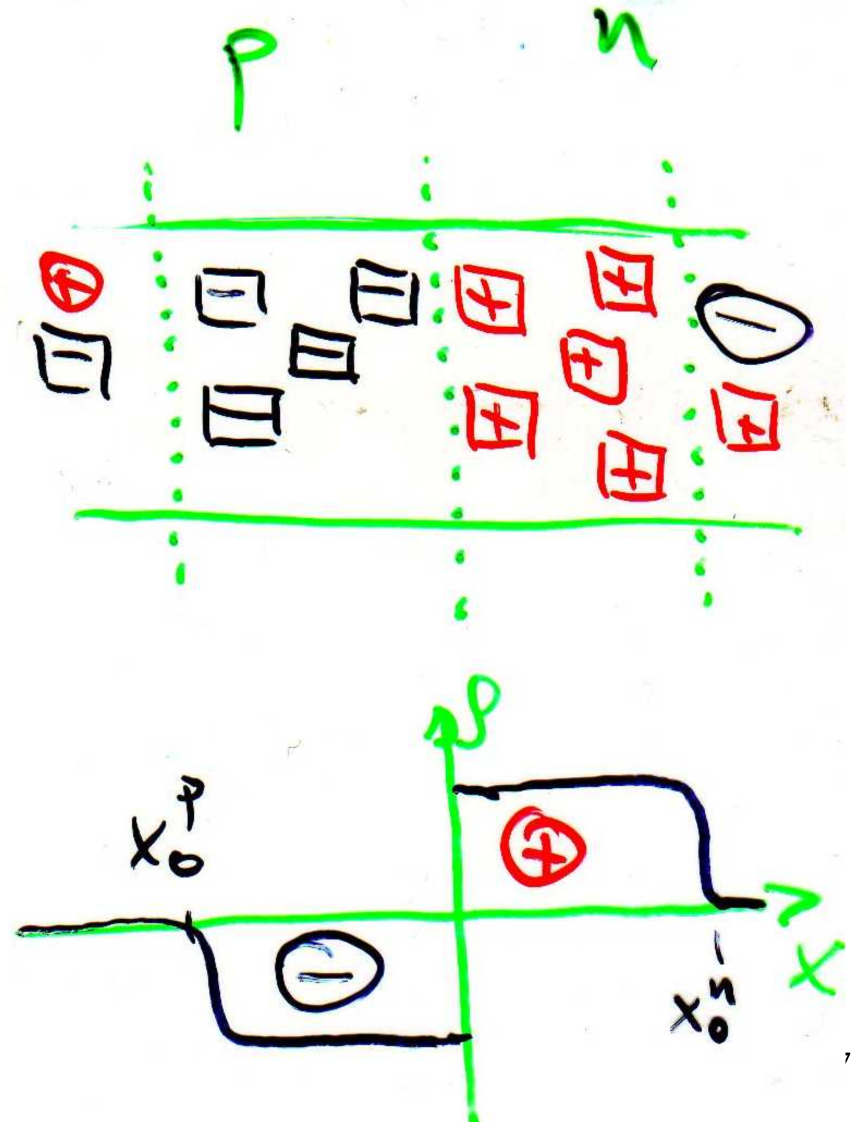
e: n→p; h: p→n

Ionen bleiben zurück

e & h rekombinieren

Raumladungszone

oder Verarmungszone



Raumladung → E-Feld → Feldstrom j_F

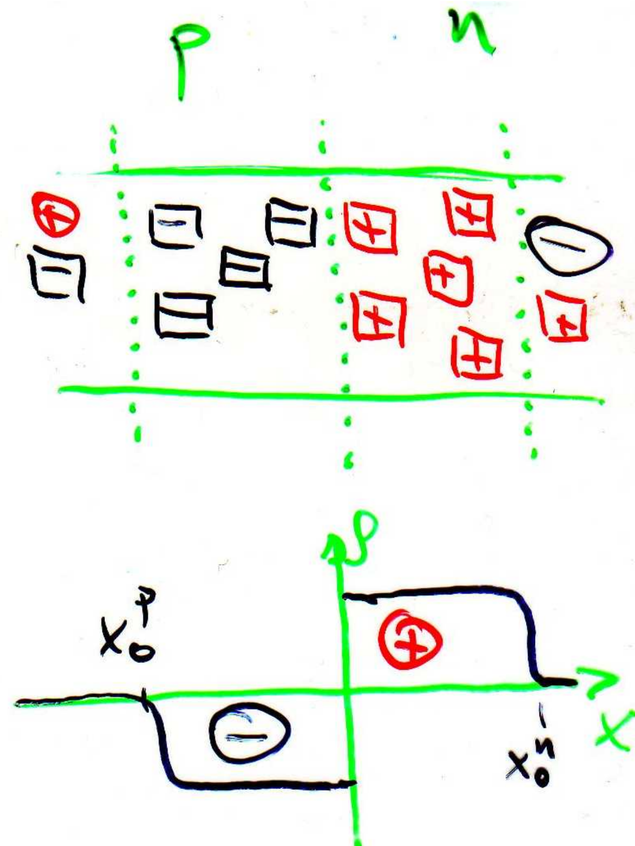
j_F ist entgegengesetzt zu j_D

→ dynamisches Gleichgewicht mit $j_D + j_F = 0$

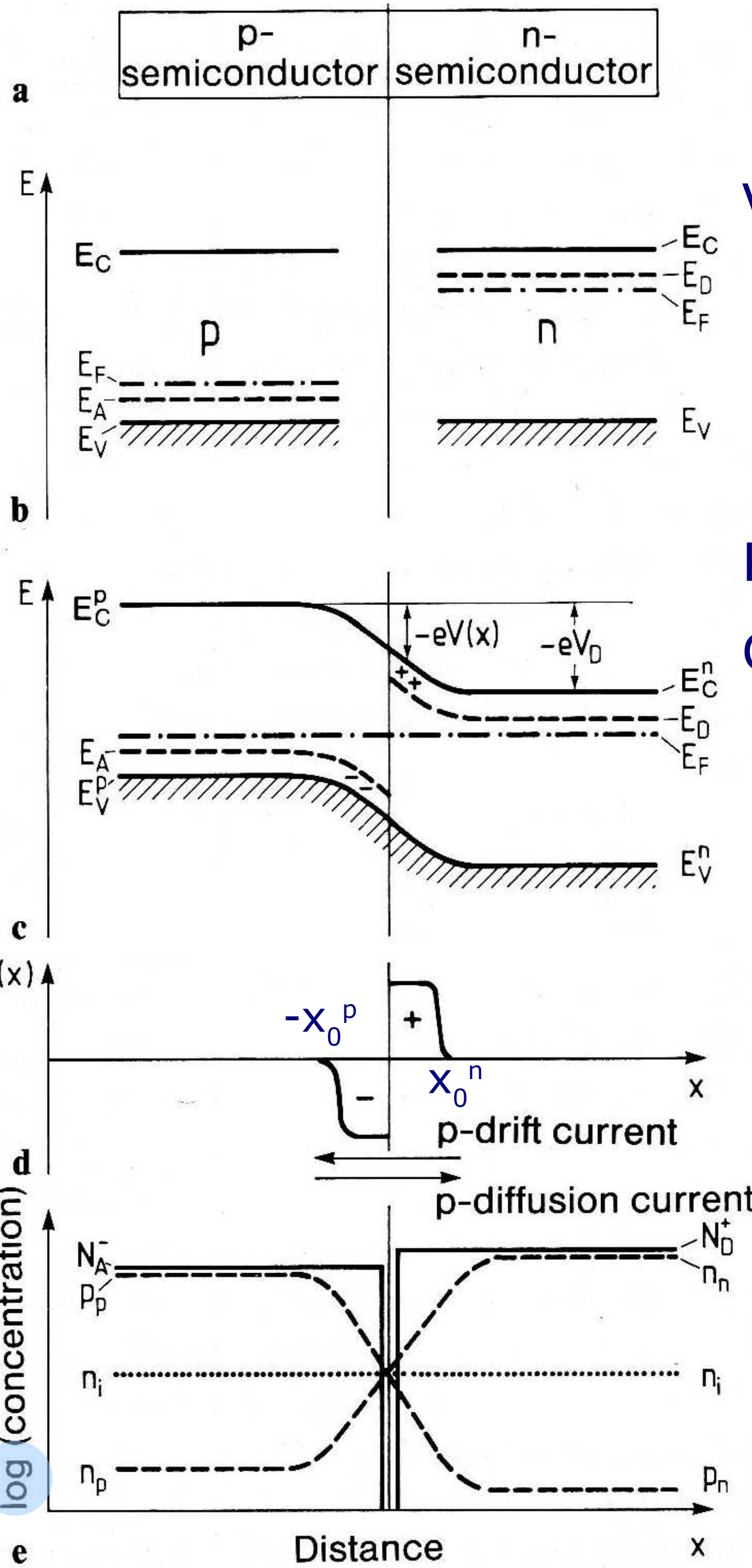
$E_F(x)$ = const.

beweglich:

fest:



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 *n/p* regions

V_D diffusion voltage

$V(x)$ macropotential of *p-n* junction

$\rho(x)$ 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 $\Rightarrow$
Bandverbiegung & Diffusionsspannung

Berechnung der Diffusionsspannung V_D

$$n_{np} = n_0 \exp\left(-\frac{E_C^{np} - E_F}{k_B T}\right) \qquad p_{np} = p_0 \exp\left(-\frac{E_F - E_V^{np}}{k_B T}\right)$$

$$n_n p_p = n_o p_0 \exp\left(-\frac{(E_C^n - E_F) + (E_F - E_V^p)}{k_B T}\right)$$

$$n_i^2 = n_n p_n = n_o p_0 \exp\left(-\frac{E_C^n - E_V^n}{k_B T}\right)$$

$$\frac{n_n p_p}{n_i^2} = \exp\left(-\frac{E_V^n - E_V^p}{k_B T}\right)$$

$$\Rightarrow \quad -V_D = \frac{E_V^n - E_V^p}{e} = \frac{k_B T}{e} \ln\left(\frac{n_n p_p}{n_i^2}\right)$$

z. B. Si bei Raumtemperatur

$p_p = N_A = 10^{18}\,\mathrm{cm}^{-3}$

$n_n = N_D = 10^{15}\,\mathrm{cm}^{-3}$

$k_B T \sim 25\,\mathrm{meV}$

$V_D = 0{,}76\,\mathrm{V}$

über welchen Bereich fällt V_D ab?

Schottkymodell

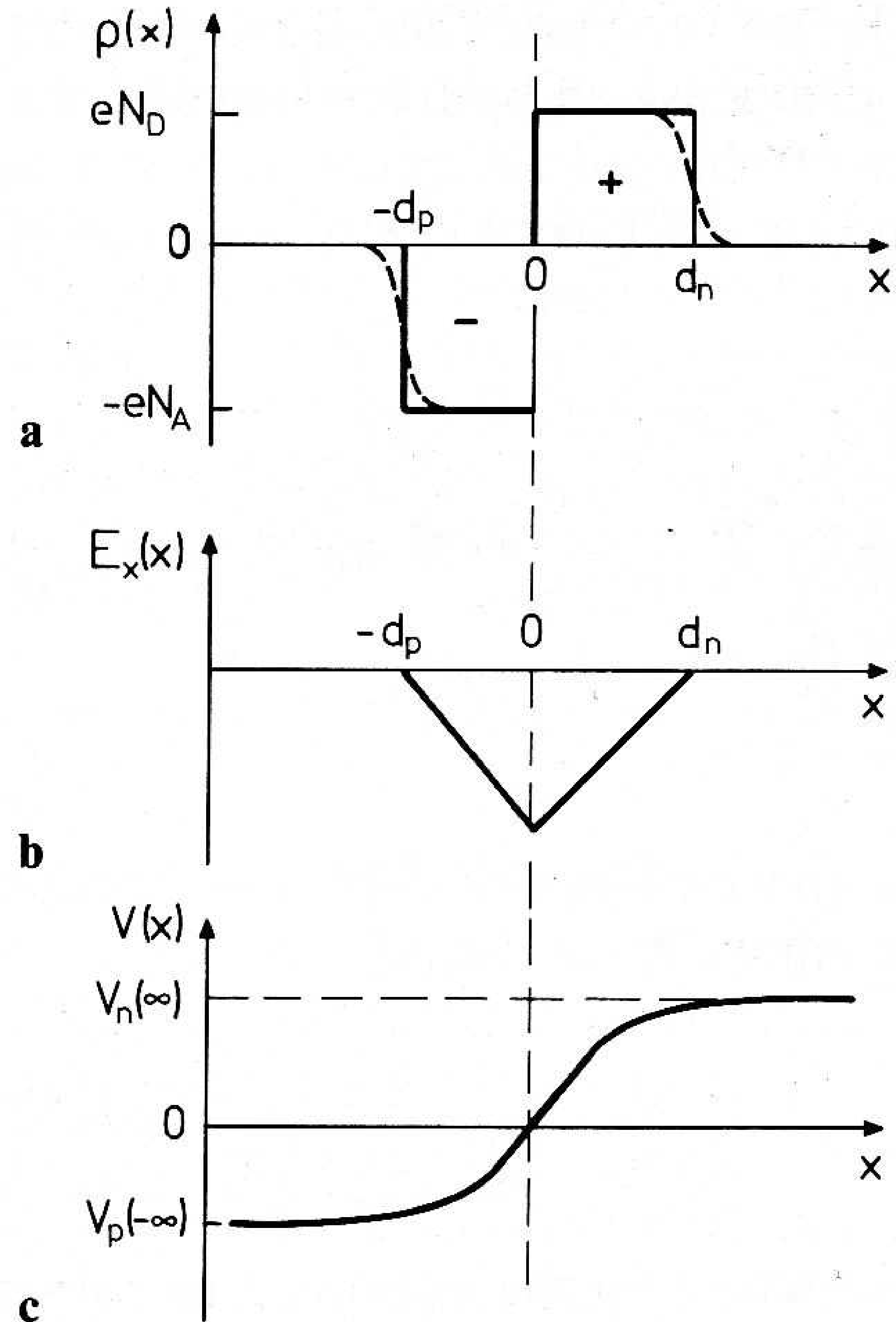


Fig. 12.16 a – c. The Schottky model for the space-charge zone of a $p-n$ junction (at $x = 0$). **a** Spatial variation of the space-charge density $\varrho(x)$ produced by the ionized acceptors (N_A) and donors (N_D). The real form of the curve (*dashed*) is approximated by the rectangular (*full line*)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

1d Poissongleichung $$V''(x) = \frac{1}{\epsilon\,\epsilon_0}\rho(x)$$

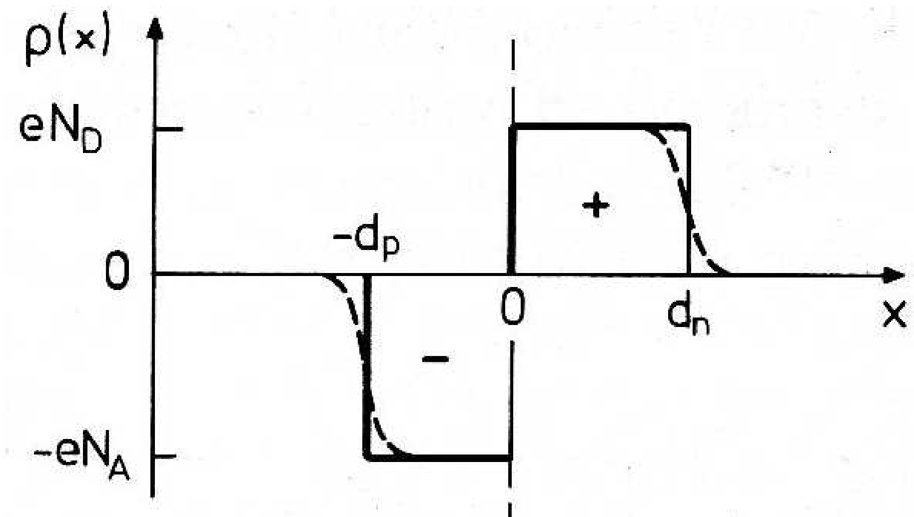
im *n*-Typ: $x>0;\quad \rho(x) = e\,(N_D^+ + p - n)$

im *p*-Typ: $x<0;\quad \rho(x) = -e\,(N_A^- + n - p)$

Neutral bei großen $|x|$: $\rho(x) = 0$

in Verarmungszone *n* und *p* klein, denn *f(E)* ist "scharfkantig"

$\rightarrow$ *ρ(x)* ist ungefähr kastenförmig



Poissongleichung integrieren ...

im p-Typ: $V''_p(x) = -\frac{1}{\epsilon\epsilon_0}N_A \quad \Rightarrow \quad V'_p(x) = -E_p(x) = -\frac{eN_A}{\epsilon\epsilon_0}x + c_p$

im n-Typ: $V''_n(x) = \frac{1}{\epsilon\epsilon_0}N_D \quad \Rightarrow \quad V'_n(x) = -E_n(x) = \frac{eN_D}{\epsilon\epsilon_0}x + c_n$

1. Randbedingung: $E_p(-d_p) = E_n(d_n) = 0$

2 Kondensatorplatten gleicher |Ladung|, außen E=0

$$\Rightarrow \quad c_{np} = -+\frac{e}{\epsilon\epsilon_0}N_{DA}d_{np}$$

$$E_p(x) = \frac{eN_A}{\epsilon\epsilon_0}(d_p + x) \qquad E_n(x) = \frac{eN_D}{\epsilon\epsilon_0}(d_n - x)$$

2. Randbedingung: keine Grenzflächenladung bei x=0

$$E_p(0) = E_n(0) = E(0) \quad \Rightarrow \quad E(0) = -\frac{e}{\epsilon\epsilon_0}N_{DA}d_{np} \qquad (0)$$

erneut integrieren ...

$$V_p(x) = \frac{1}{2}\frac{e}{\epsilon\epsilon_0}N_A(d_p+x)^2+\tilde{c}_p \qquad V_n(x) = -\frac{1}{2}\frac{e}{\epsilon\epsilon_0}N_D(d_n-x)^2+\tilde{c}_n$$

Randbedingung: wähle Potentialnullpunkt $0 = V_n(0) = V_p(0)$

$$\Rightarrow \quad V_{np}(x) = -+\frac{1}{2}\frac{e}{\epsilon\epsilon_0}N_{DA}\left[(d_{np}-+x)^2-d_{np}{}^2\right]$$

d_{np} aus V_D bestimmen: (U von außen angelegt)

$$V_D-U = V_n(d_n)-V_p(-d_p) = \frac{1}{2}\frac{e}{\epsilon\epsilon_0}\left(N_D d_n^2-N_A d_p^2\right) \qquad (1)$$

zusätzlich Neutralität:

$$e\,d_n N_D = e\,d_p N_A \qquad (2)$$

(1) und (2) $\rightarrow$ Ausdehnung der Raumladungszone

$$d^{(n)} = \frac{N_A}{N_D} d^{(p)} = \sqrt{2 \frac{\epsilon \epsilon_0}{e} (V_D - U) \frac{N_A}{N_D} \frac{1}{N_A + N_D}} \qquad (3)$$

Mit (0) $E(0) = \frac{e}{\epsilon \epsilon_0} N_A d_p = \frac{e}{\epsilon \epsilon_0} N_D d_n$ $\rightarrow$ Feldstärke am Übergang

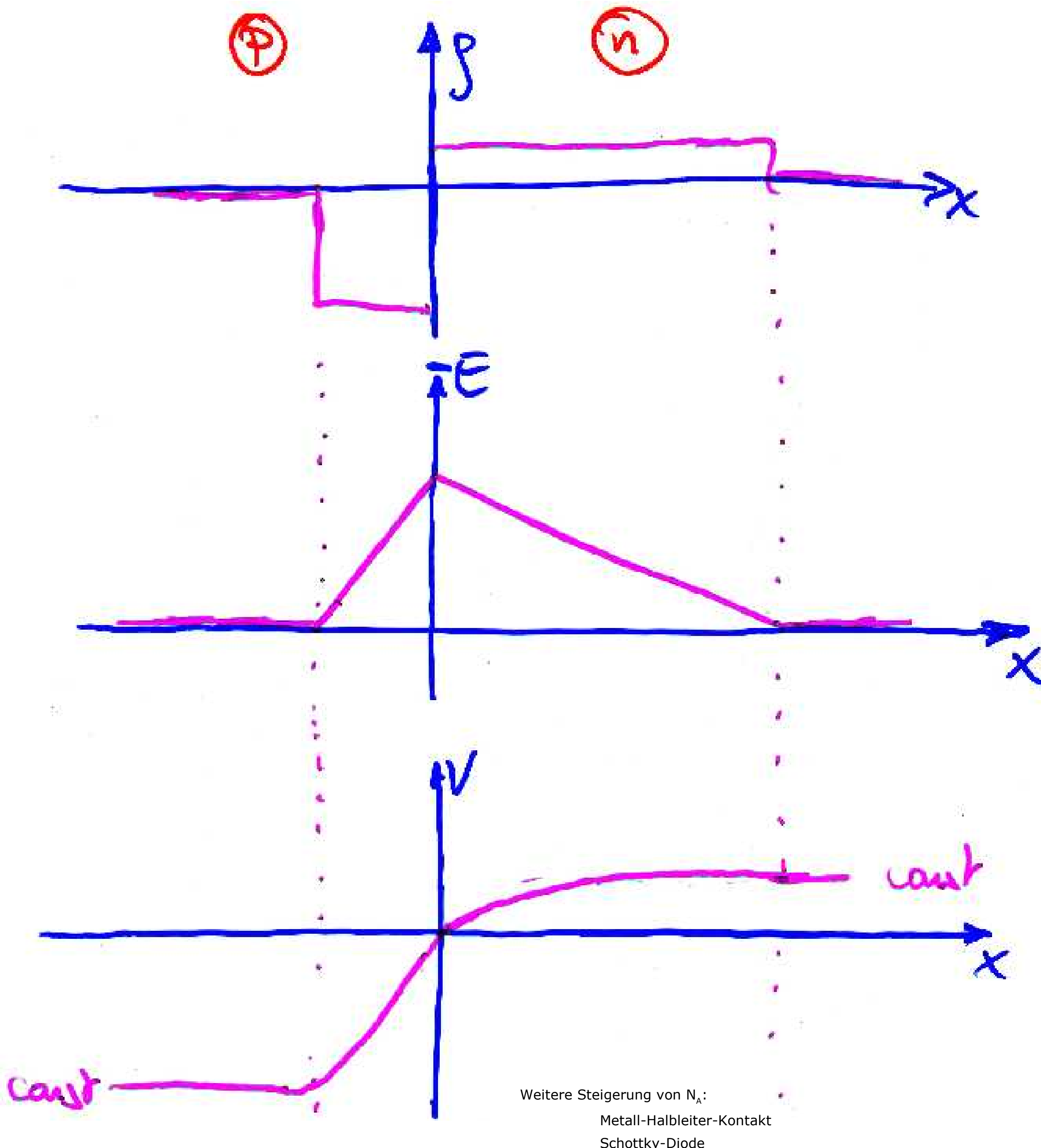
$$E(0) = \sqrt{2 \frac{e}{\epsilon \epsilon_0} (V_D - U) \frac{N_A N_D}{N_A + N_D}} \qquad (4)$$

(0) $\rightarrow$

$$d_p + d_n = \frac{\epsilon \epsilon_0}{e} E(0) \left(\frac{1}{N_A} + \frac{1}{N_D} \right) = \frac{\epsilon \epsilon_0}{e} E(0) \frac{N_A + N_D}{N_A N_D}$$

In (4) $\rightarrow$ $E(0) = 2 \frac{V_D - U}{d_p + d_n}$

Resultat für $N_A \gg N_D$



Weitere Steigerung von N_A:

Metall-Halbleiter-Kontakt

Schottky-Diode

Wertebeispiel: Si bei 300 K

d_n = 1 µm

d_p = 1 nm

$E(0)$ = 1.5x10^4 V/cm

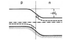
Mit Sperrspannung U = -50 V

d_n = 8 µm

d_p = 8 nm

$E(0)$ = 1.2x10^5 V/cm

Durchbruch bei ca. 3x10^5 V/cm



jetzt Poisson #1, #2

Debysche Abschirmlänge

Wie gut ist die Kastennäherung?

$$\lambda = \sqrt{\frac{\epsilon\epsilon_0}{e^2} k_B T \frac{1}{n}}$$ *(oder 1/p)*

Schottkymodell o.k., wenn

$$\lambda_D \ll d_n, d_p$$

gegeben Flächenladung bei $x = 0$

$$x>0: \quad V''(x) = \frac{e}{\epsilon\epsilon_0}\left(n(x) - n_\infty\right) = \frac{e}{\epsilon\epsilon_0}\left(n_\infty \exp\left(\frac{eV}{k_B T}\right) - n_\infty\right)$$

$\exp(x) - 1 \approx x$

$$\Rightarrow \quad V''(x) \approx \frac{e}{\epsilon\epsilon_0} n_\infty \frac{eV}{k_B T} \quad \Rightarrow \quad V''(x) = A \exp\left(-\frac{x}{\lambda_D}\right) + B$$

Für Si-Beispiel: $\lambda_p \sim 4$ nm < 8 nm $= d_p$ *10^{18}*

$\lambda_n \sim$ *120* nm $<< 8$ µm $= d_n$ *10^{15}*

Näherung o.k. für kleine Dotierungen

Kapazität des *pn*-Übergangs

Plattenkond.:

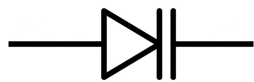
$$E = \frac{1}{\epsilon \epsilon_0} \frac{|Q|}{A}$$

$$\frac{|Q|}{A} = e N_D d_n \qquad \frac{|Q|}{A} = \epsilon \epsilon_0 E(0) = \sqrt{2 \epsilon \epsilon_0 e \frac{N_A N_D}{N_A + N_D} \underbrace{(V_D - U)}_{V_t}}$$

differentielle Kapazität pro Fläche:

$$\tilde{C} = \frac{1}{A} \frac{dQ}{dV_t} = \sqrt{\frac{1}{2} \epsilon \epsilon_0 e \frac{N_A N_D}{N_A + N_D}} \frac{1}{\sqrt{V_t}}$$

→ Kapazitätsdiode



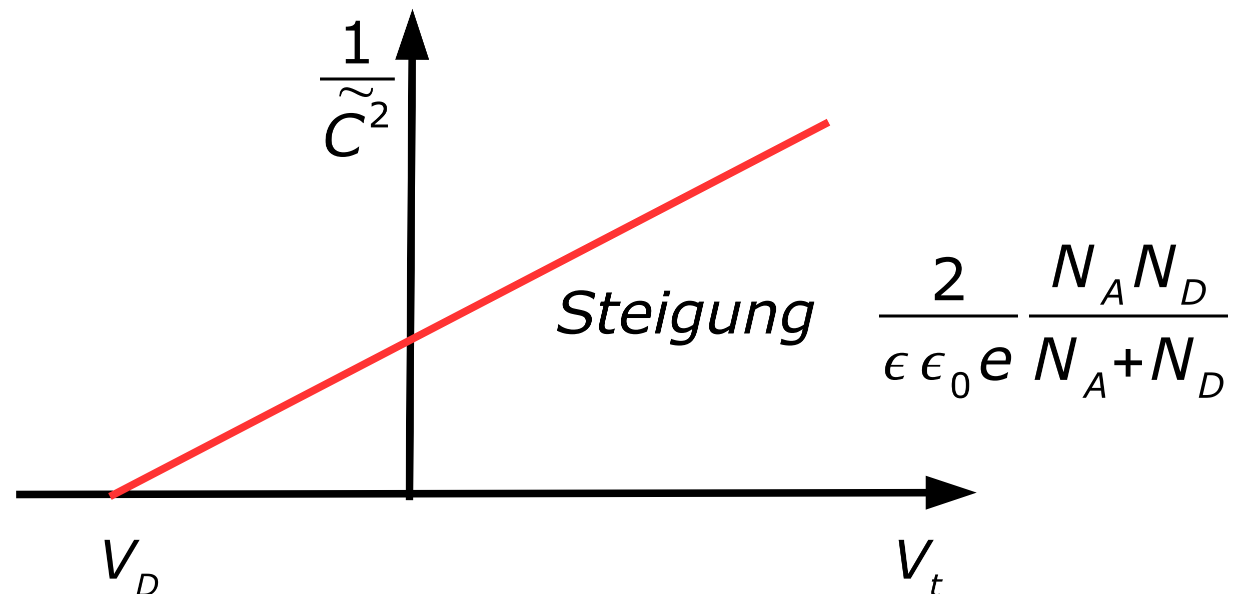
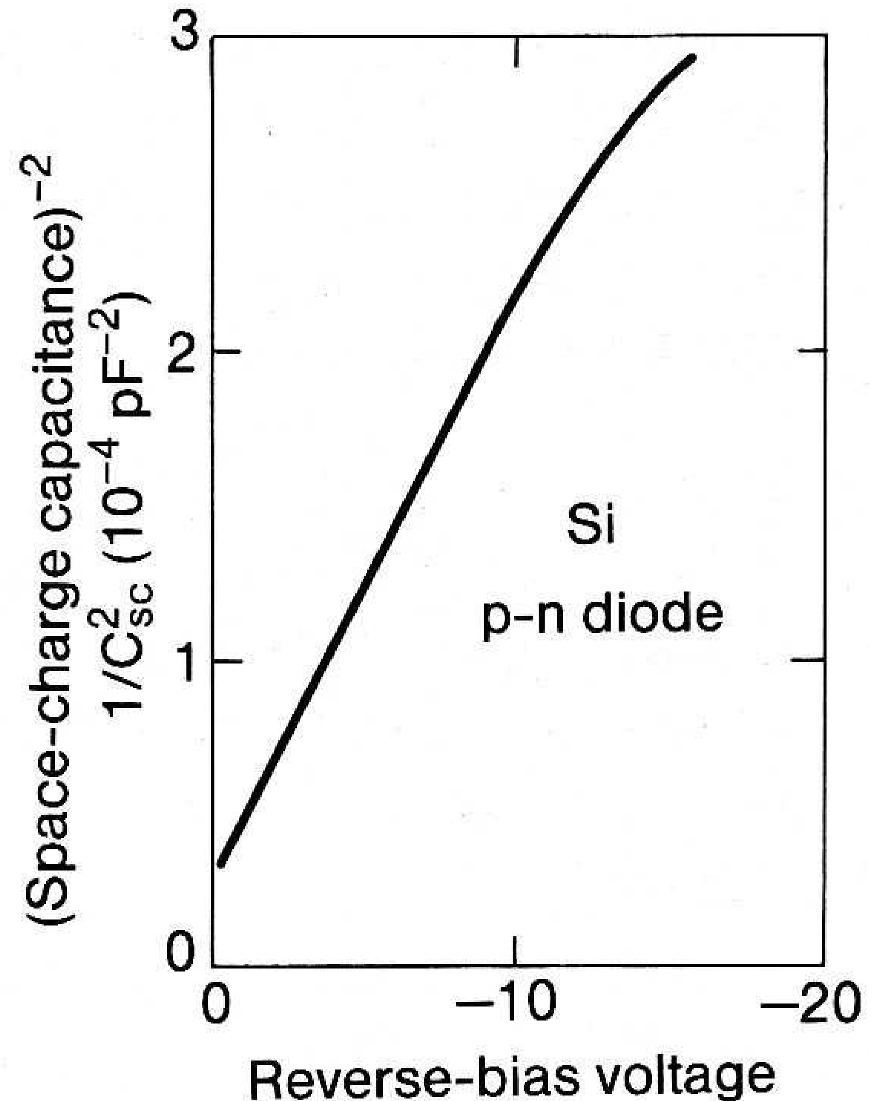


Fig. 12.20. Experimentally determined relationship between the space-charge capacitance and the reverse voltage (indicated by negative values) for the Si $p-n$ diode discussed in Fig. 12.19. (From the advanced lab. course of the II. Physics Institute of the RWTH Aachen)



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

Forward bias

p n

+ −

Reverse bias

p n

− +

Current (μA)

10^{2} 10^{1} 1 10^{-1} 10^{-2}

-10^{-3} -10^{-2} -10^{-1}

-60 -40 -20 0 0.1 0.2 0.3 0.4 0.5

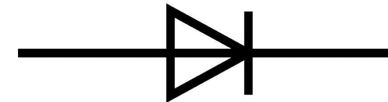
Reverse-bias voltage (V) Forward-bias voltage (V)

Fig. 12.19 Ibach-Lüth

Lab course

II. Physikalisches Institut
RWTH Aachen

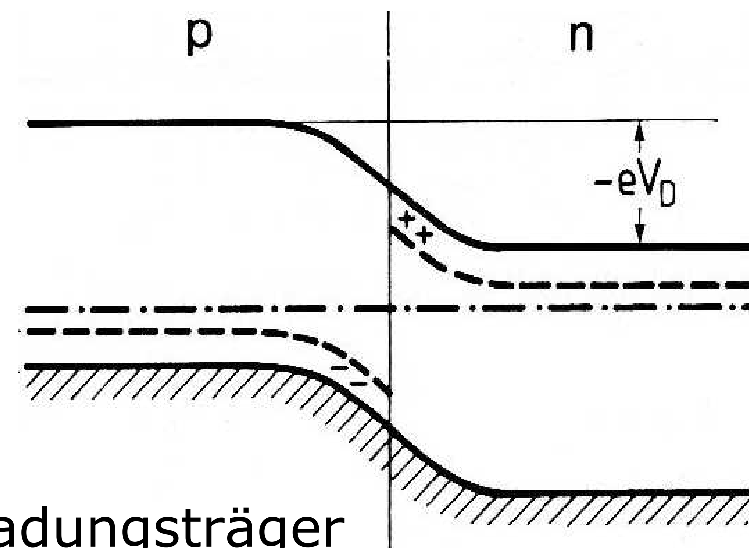
Rectification



jetzt Poisson #4

Ströme durch *pn*-Übergang

zu betrachten e und h, hier e:



im *p*-HL:

e entstehen thermisch, sind dort Minoritätsladungsträger

spüren V_D

wg. Verarmung keine h zur Rekombination: ''alle'' e erreichen *n*-HL

$\rightarrow$ Feldstrom oder Generationsstrom

im *n*-HL:

hier viele e: Majoritätsladungsträger

diffundieren gegen V_D in den *p*-HL, Erfolgswahr. $\propto \exp\left(-\frac{e}{k_B T}(V_D - U)\right)$

rekombinieren im *p*-HL

$\rightarrow$ Diffusionsstrom oder Rekombinationsstrom

$$I_e^{rec} \propto \exp\left(-\frac{e}{k_B T}(V_D - U)\right) \qquad I_e^{rec}(U=0) \approx I_e^{gen}$$

$$\Rightarrow \quad I_e^{rec} = I_e^{gen} \exp\left(-\frac{e}{k_B T}(V_D - U)\right)$$

$$\Rightarrow \quad I_e = I_e^{rec} - I_e^{gen} = I_e^{gen}\left[\exp\left(-\frac{e}{k_B T}(V_D - U)\right) - 1\right]$$

Ebenso für Löcherströme.

$$\Rightarrow \quad I(U) = (I_e^{gen} + I_h^{gen})\left[\exp\left(-\frac{e}{k_B T}(V_D - U)\right) - 1\right]$$

Shockleygleichung

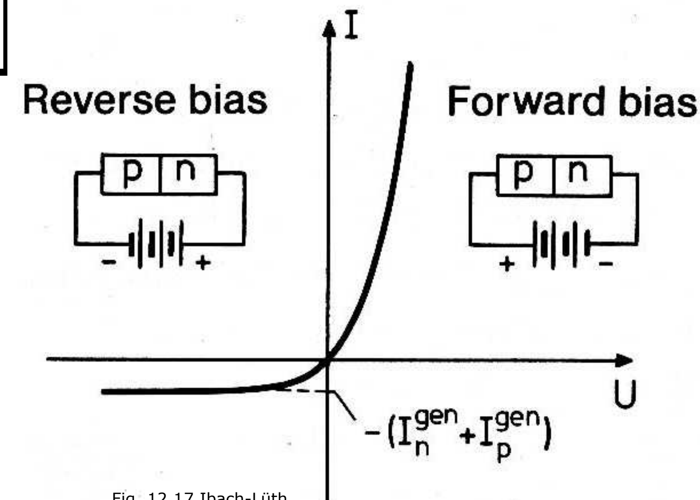
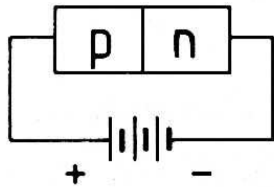


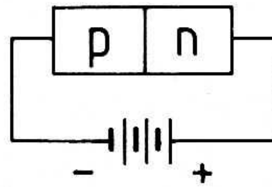
Fig. 12.17 Ibach-Lüth

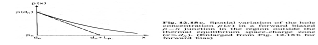
Non-equilibrium situation: Quasi Fermi levels

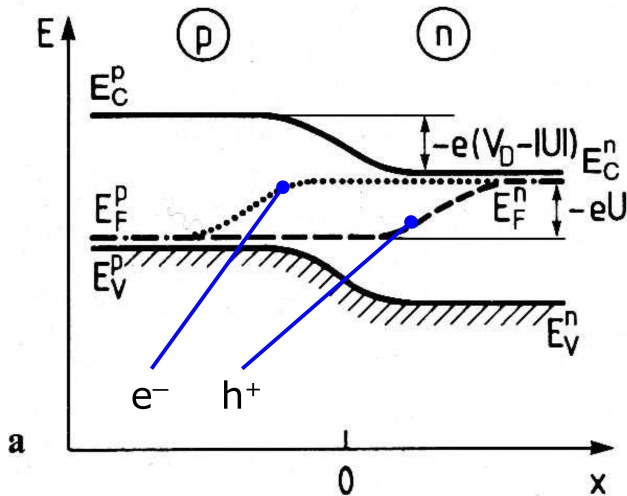
Forward bias

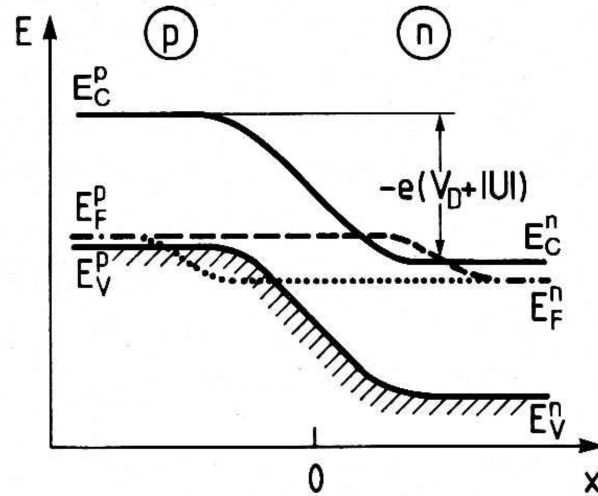


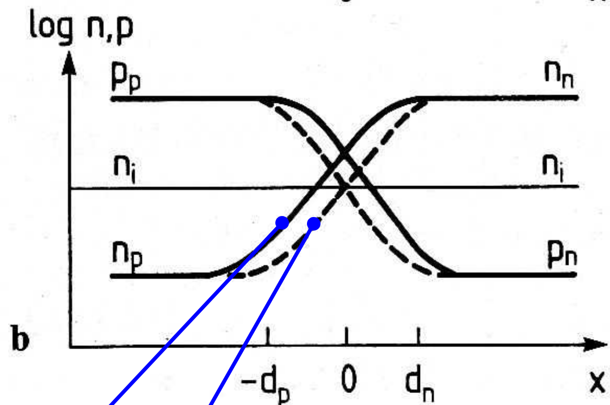
Reverse bias











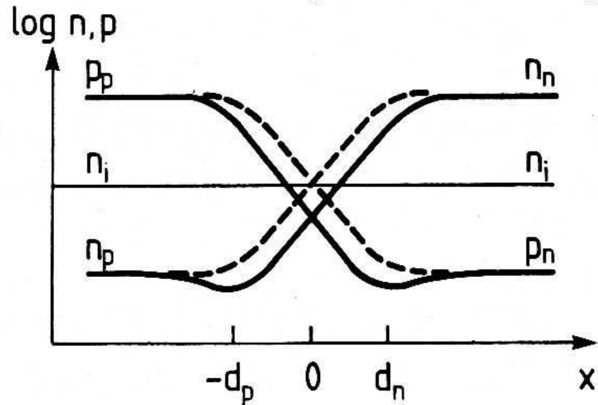
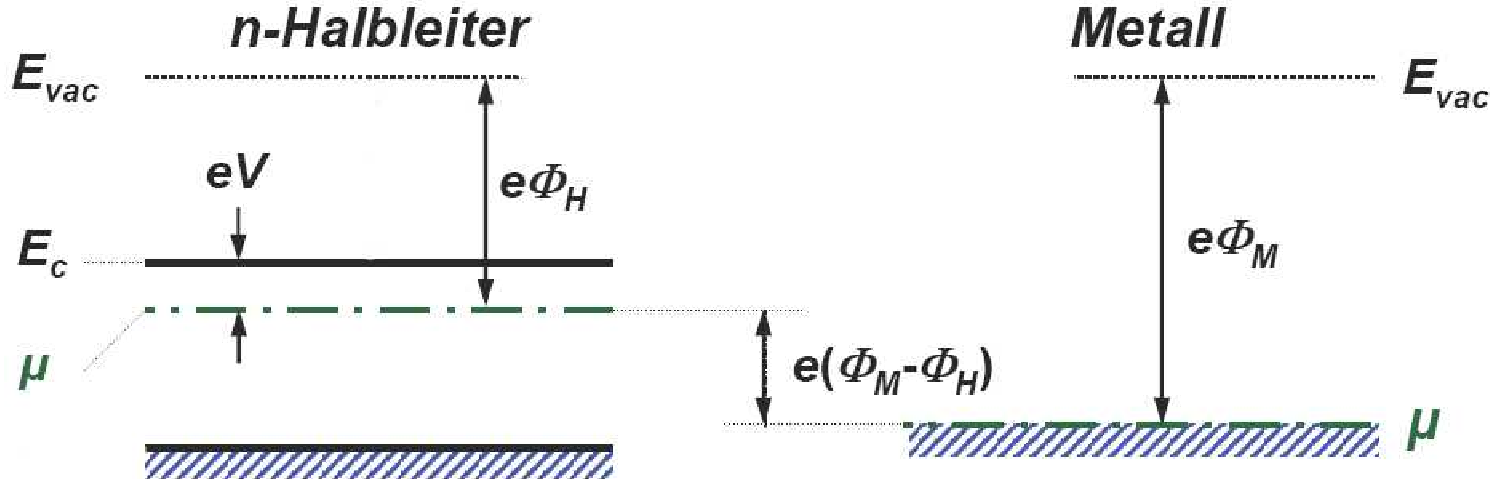


Fig. 12.18 a, b. Forward- and reverse-biased $p-n$ junctions (non-equilibrium state). **a** Band scheme in the presence of an external voltage $+U$ or $-U$. The Fermi levels E_F^p and E_F^n in the p and n regions are shifted with respect to one another by eU. In the region of the $p-n$ junction, the equilibrium Fermi level (−·−) splits into so-called quasi Fermi levels for electrons (···) 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

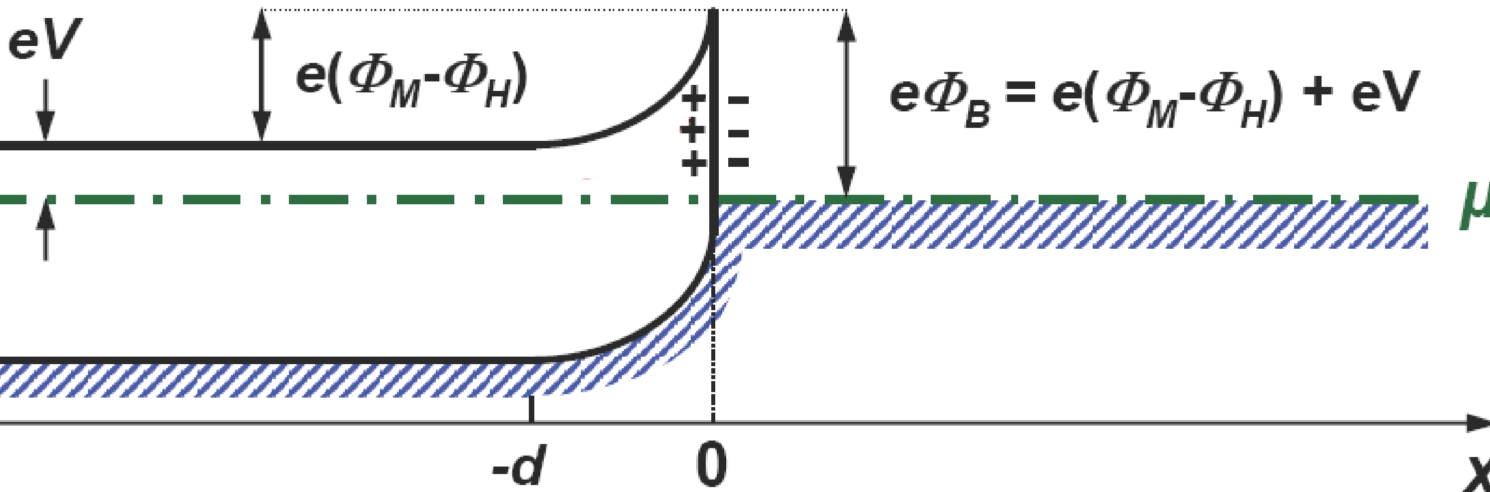
Ohne Drähte geht's nicht: Schottky-Kontakt

getrennt

V: ext. Spannung



Kontakt

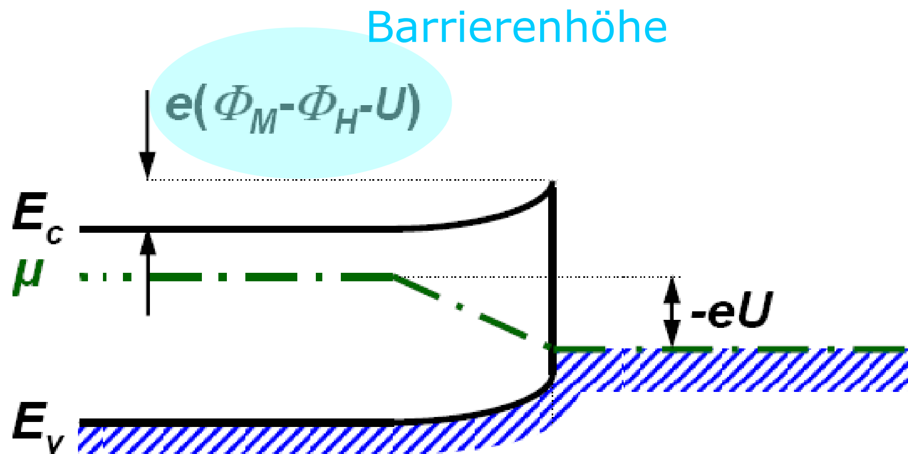


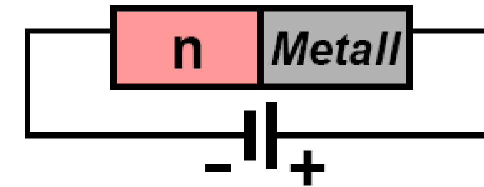
Kontaktpotential: $V_K = e\ (\Phi_M - \Phi_H)$

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

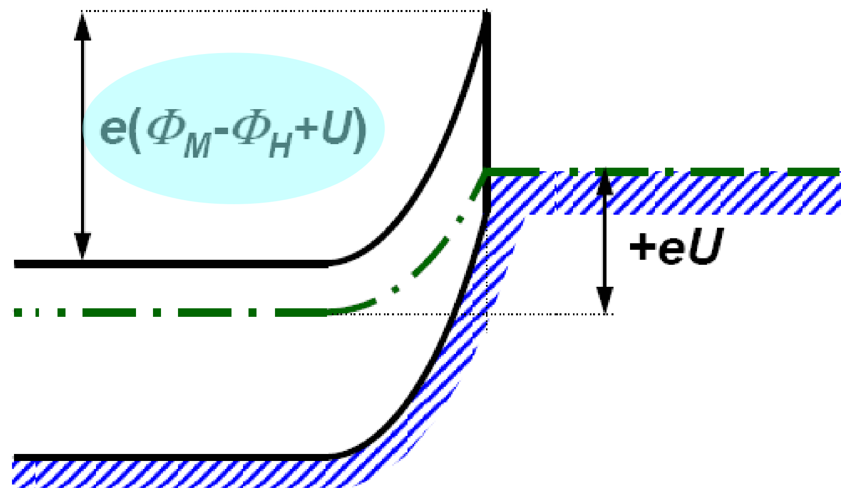
$V(0) = V_K + V$ also $d(U{=}0) = (\ (2\varepsilon\varepsilon_0)/(e\ N_D)\ V_K\ )^{1/2}$

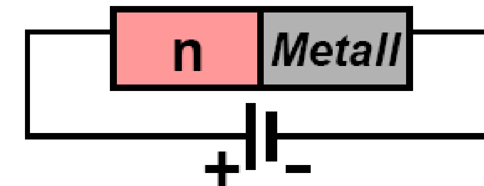
Schottkydiode (im Schottkymodell)



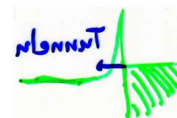


Durchlassrichtung





Sperrichtung



Ohmsch bei großem N_D (Tunneln)

Abweichungen vom Shockley-Modell

Zuleitungswiderstände

Oberflächenkanäle

Erzeugung/Vernichtung

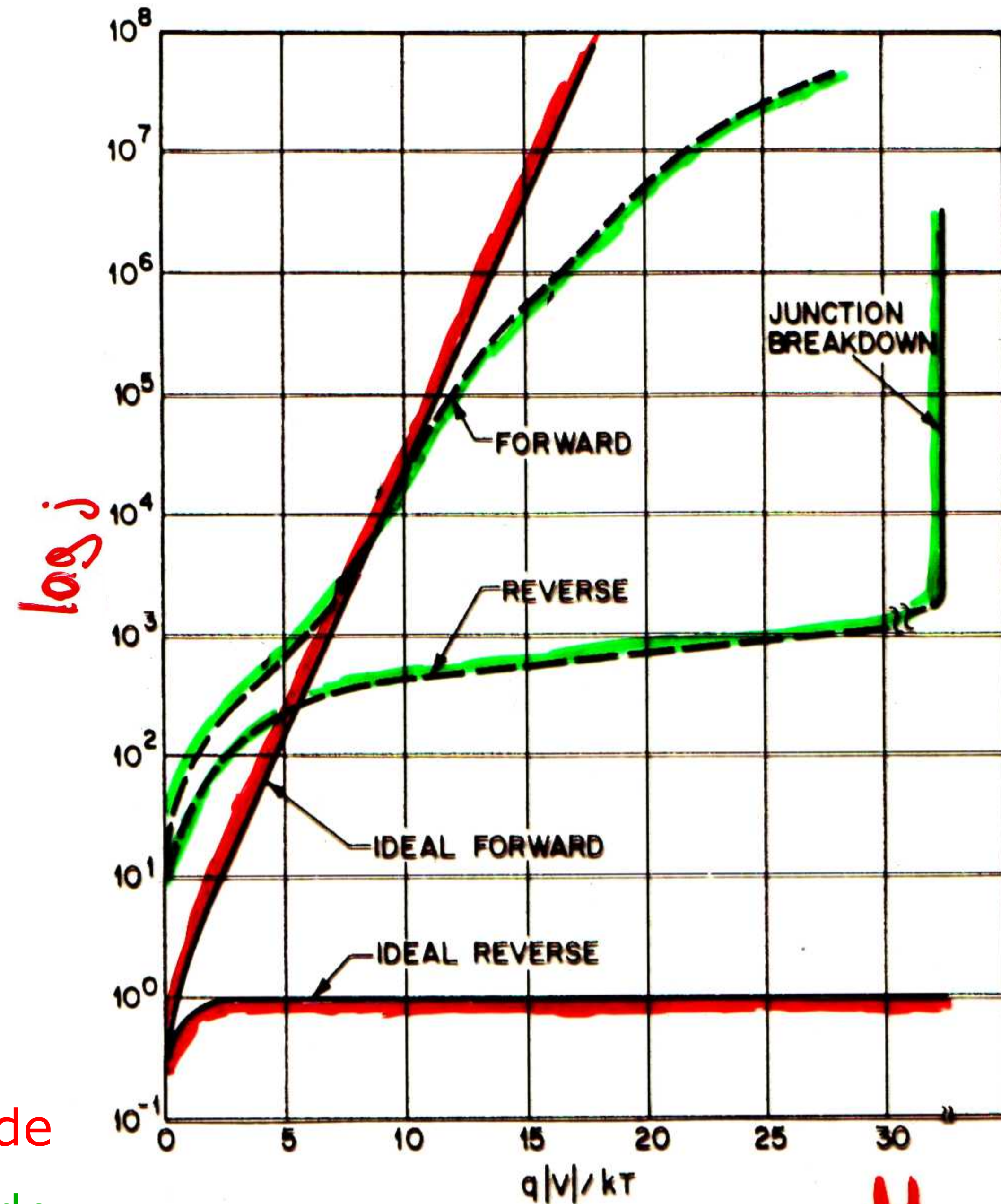
in Verarmungszone

Tunneln

starke Injektion

(i. e. Dichte von eindiffundierenden

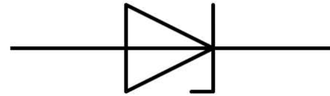
e^- im *p*-Bereich mit *n* vergleichbar)

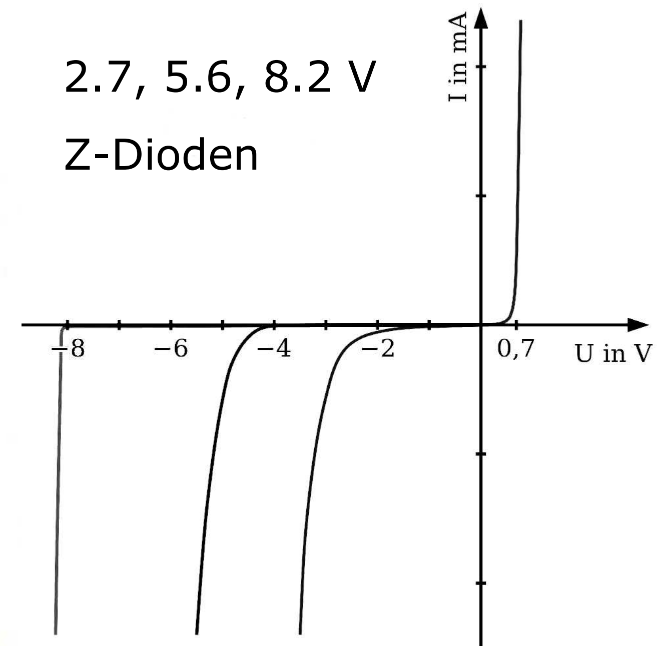


Shockley-Diode

reale Si-Diode

Zener-Diode





$\tilde{W}_n$

Leitungsband

Valenzband

$\tilde{W}_L = W_L - eEz$

$\tilde{W}_V = W_V - eEz$

Δz

z_1 z_2 z

Abb. 8.19
Zum Zener-Effekt

Bei hoher Sperrspannung:

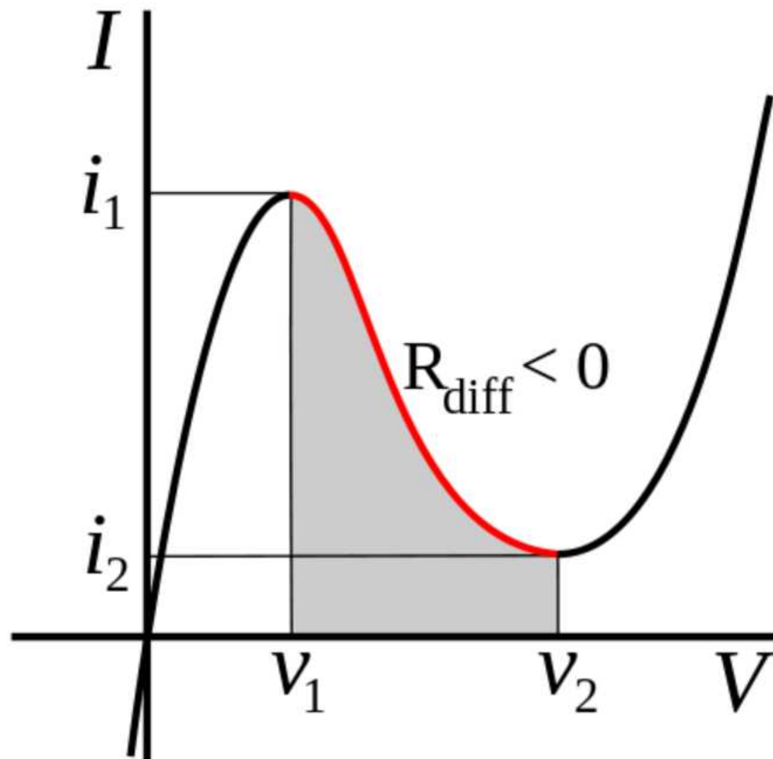
Tunneln durch Verarmungszone.

⇒ 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

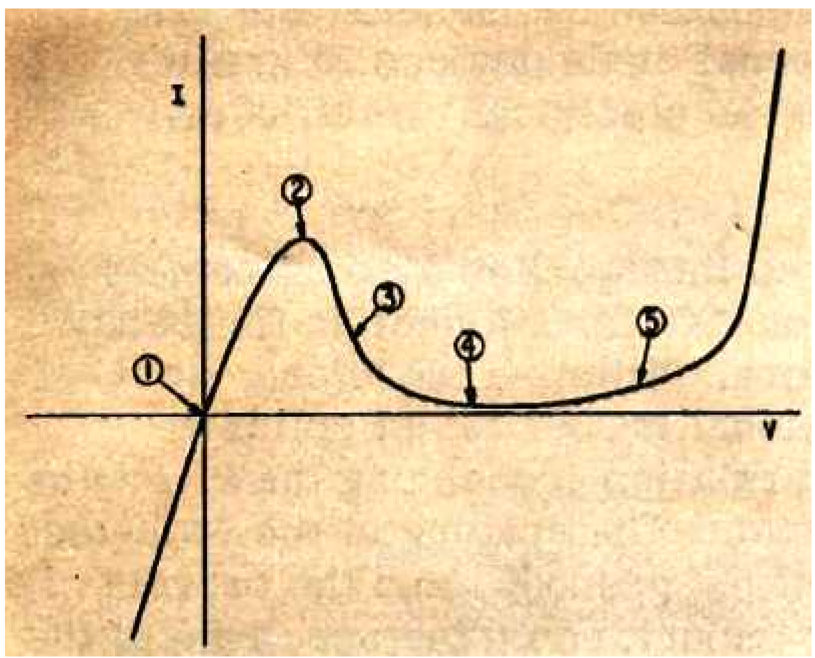


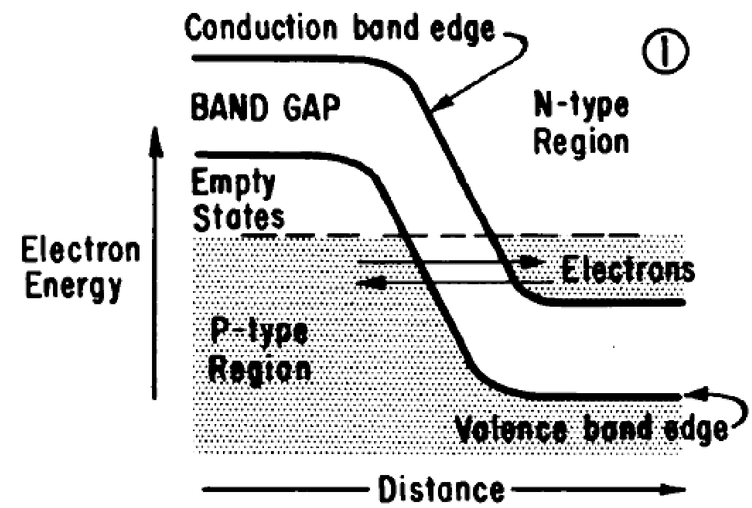
FIGURE 2

CURRENT-VOLTAGE CURVE

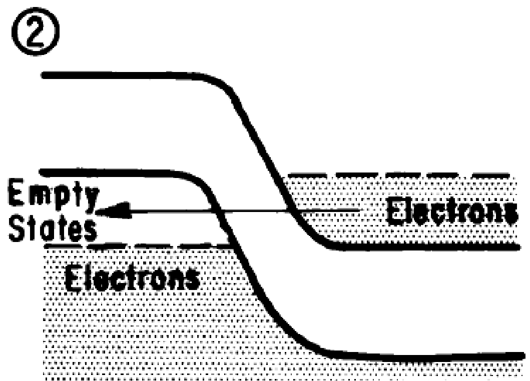
FIGURE 1

TUNNEL DIODE JUNCTION AT VARIOUS BIAS CONDITIONS

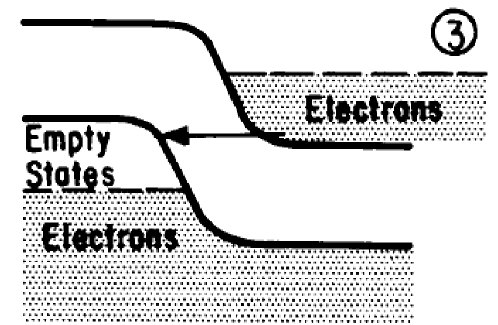
(The numbered diagrams below correspond to the numbered points on the current-voltage curve, Figure 2.)



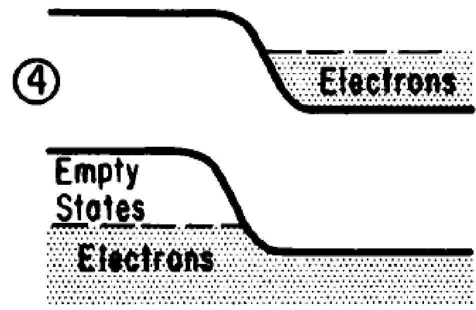
Electrons at same level on both sides of junction. No net current.



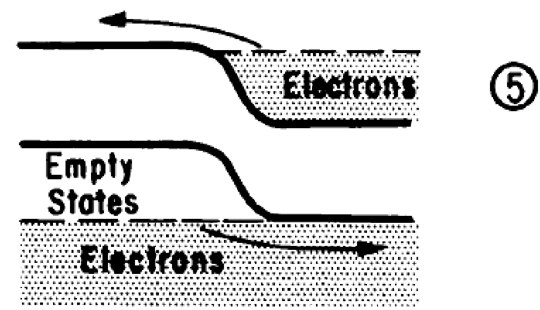
Electrons on right side are raised until they are opposite empty states on left side. Strong current flows from right to left.



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



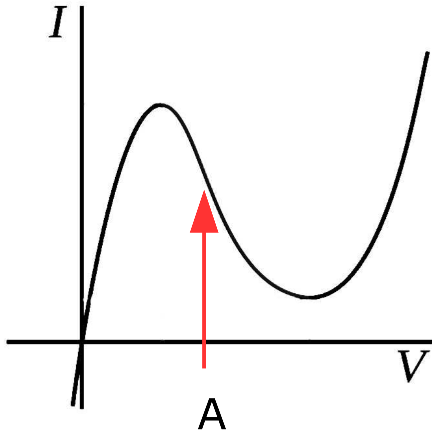
Electrons all are opposite forbidden gap. Very small current.

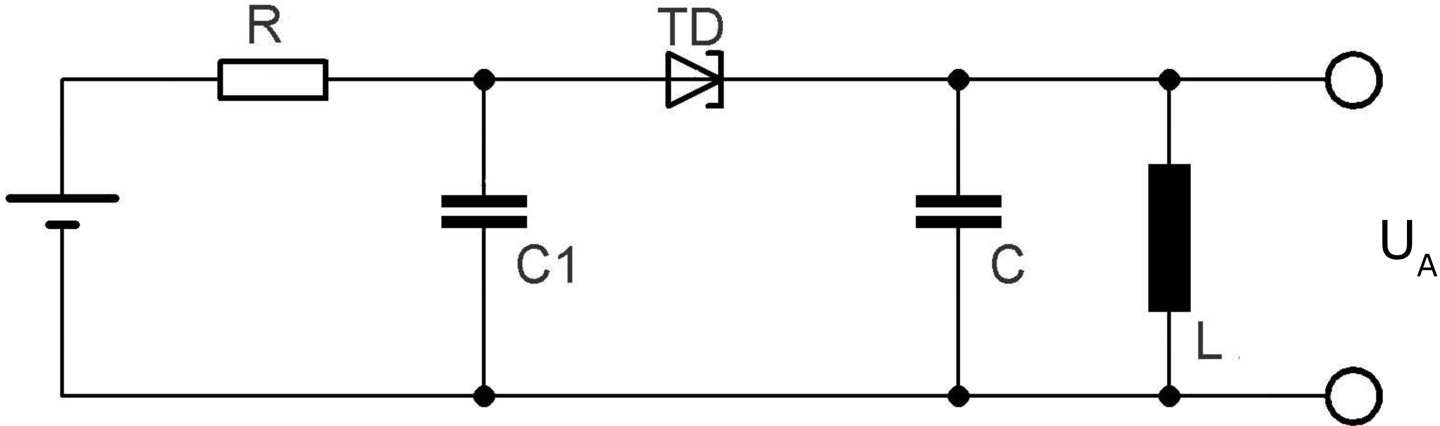


Electrons raised until they spill over barrier. Current increases.

Oszillator mit Tunneldiode

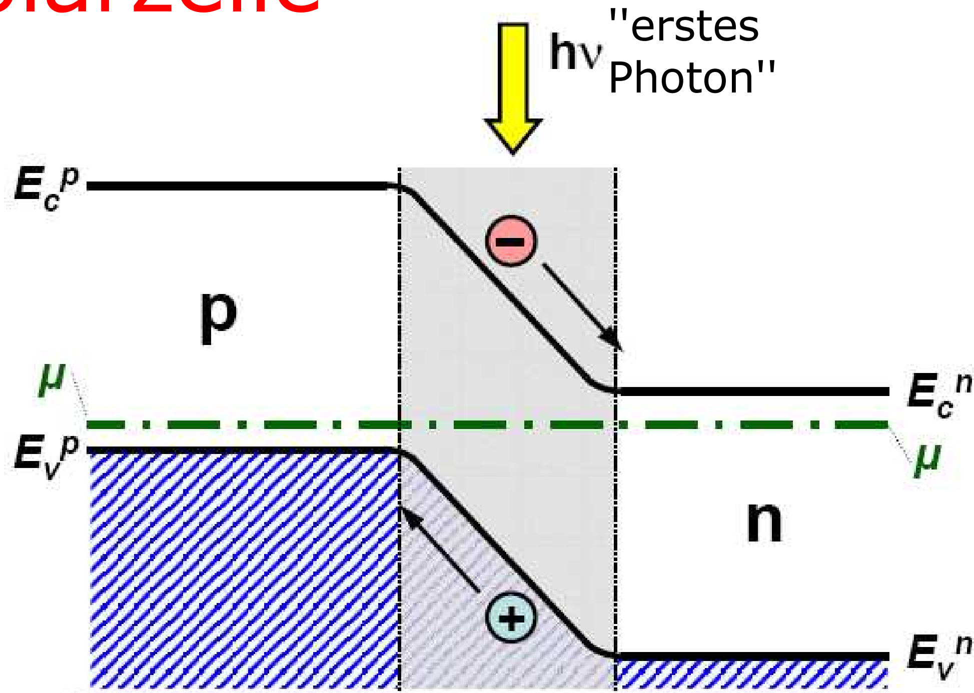
aus: Tietze-Schenk, 1969er Ausgabe

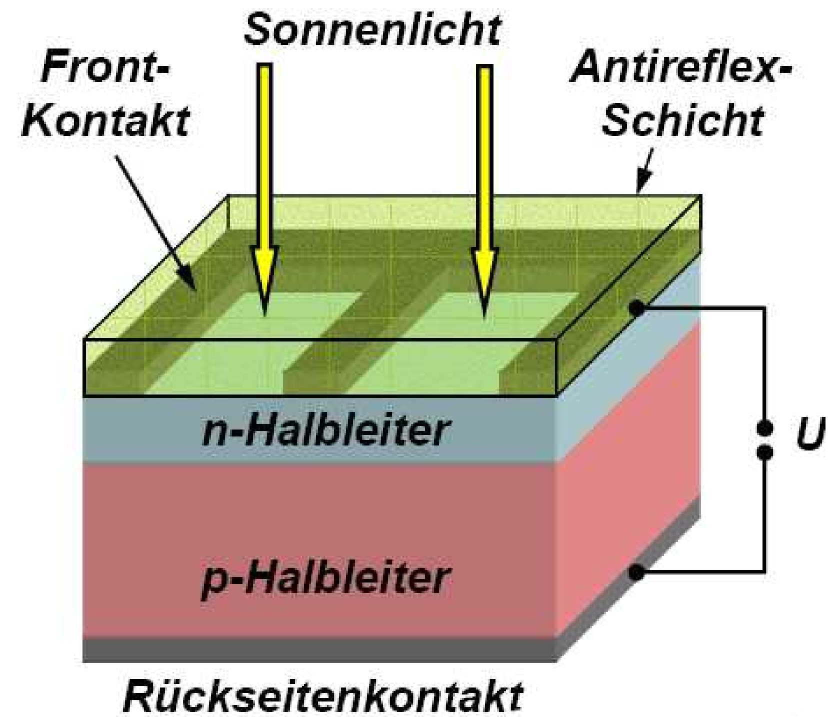


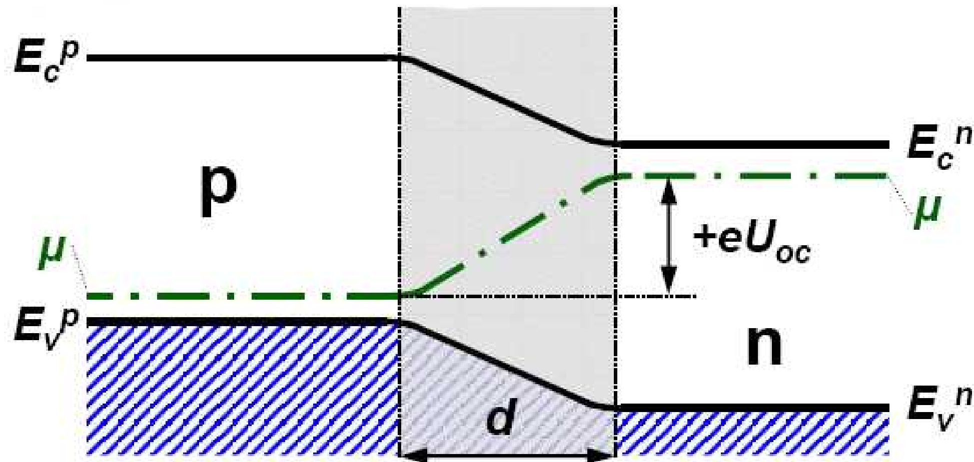


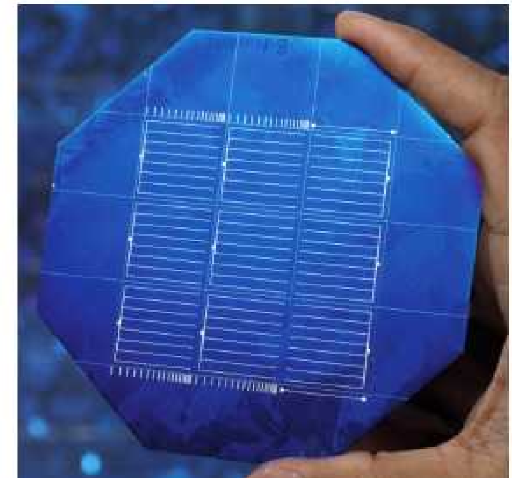
gkreis

Solarzelle









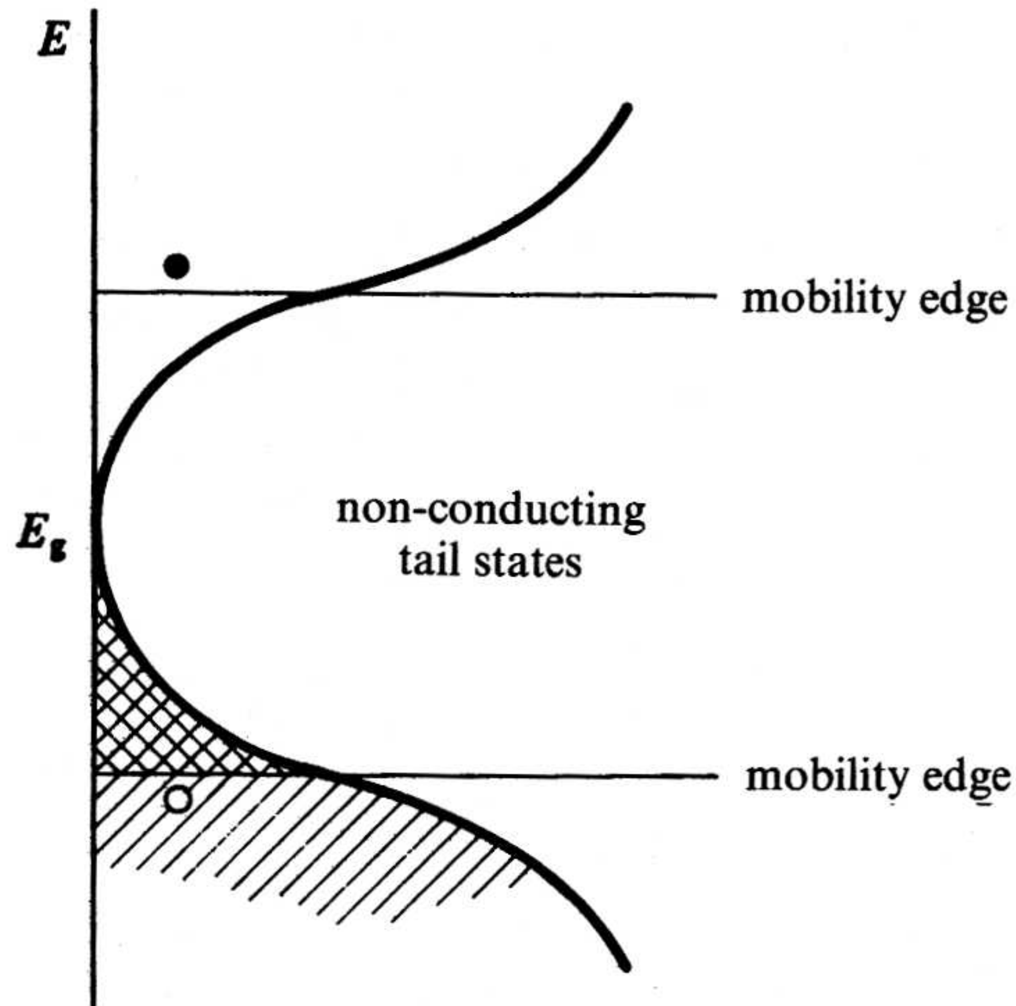
viel Licht: Spannung U_{oc} (open circuit)

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

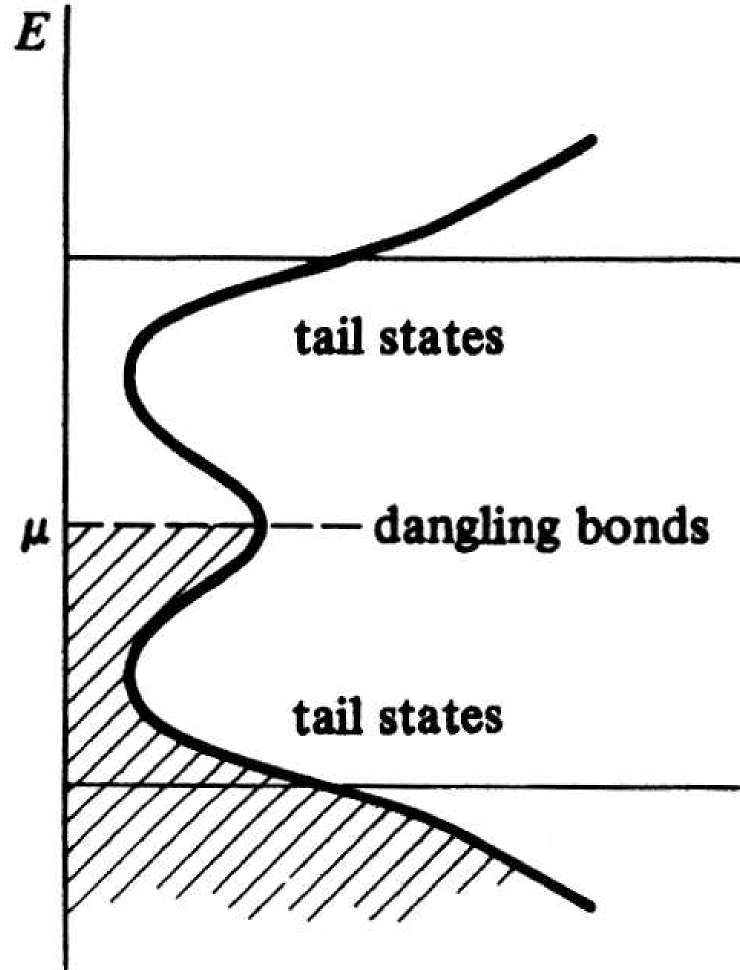
Einfluss von Unordnung



10.16 Marder

In a fully coordinated but distorted tetrahedral semiconductor like Si, disorder causes a spread of the levels into the region of the energy gap of the perfect crystal. These so-called tail states arise from the distorted bonds and are considered to be localized and non-conducting. The energy gap is replaced by a mobility gap.

Amorpher Halbleiter (preisgünstige Solarzellen)



10.17 Marder

In practice an amorphous semiconductor contains imperfectly coordinated atoms, leading to uncompensated or 'dangling' bonds. Each such bond produces a localized electron and a localized empty state. On account of their quasi-atomic character, these states are concentrated about the middle of the energy gap; they are sufficiently numerous to lock E_F at 1/2 E_g. As a consequence, the amorphous semiconductor becomes insensitive to doping.

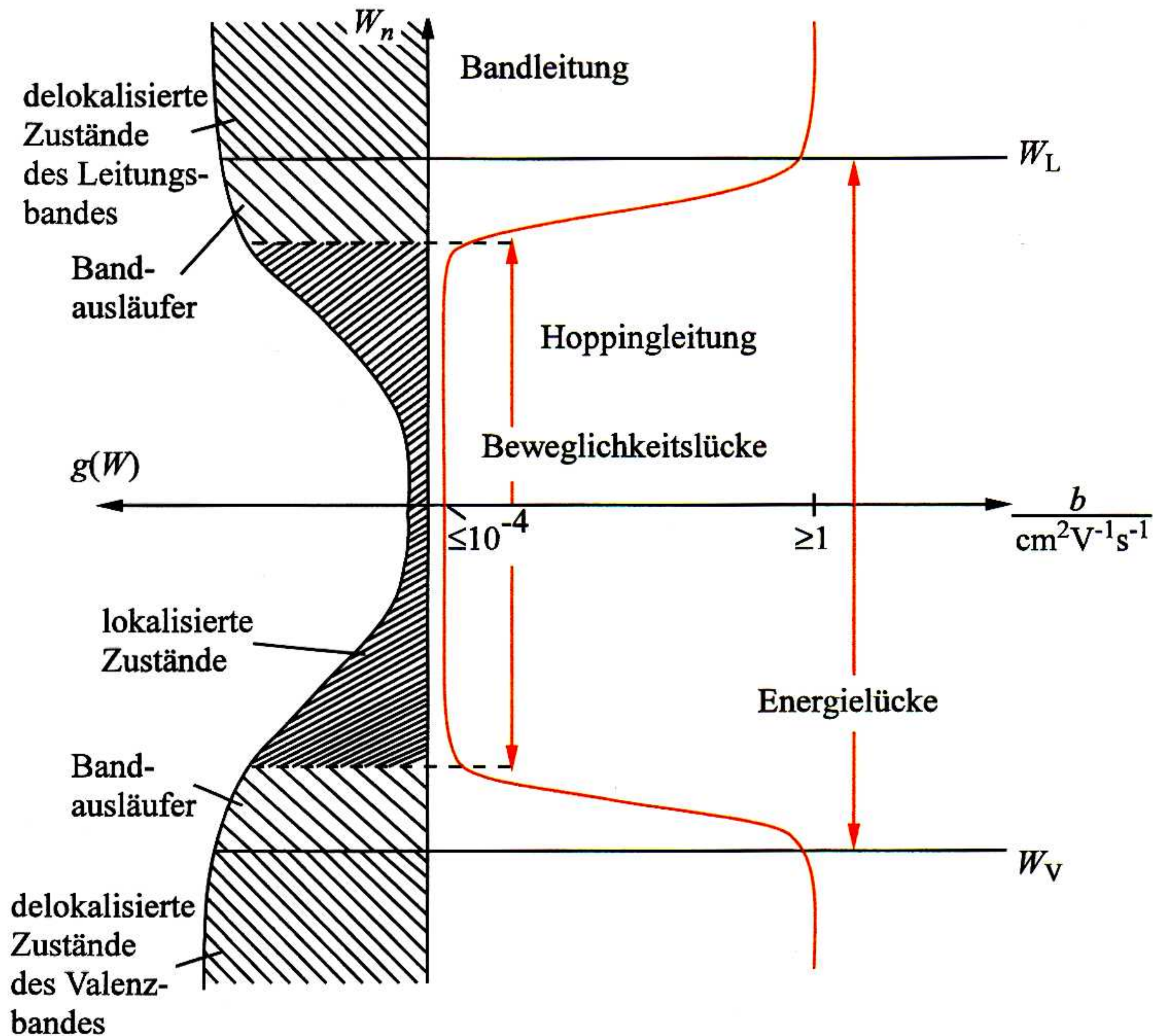


Abb. 7.22
Energiezustände W_n, Zustandsdichte $g(W)$ und Beweglichkeit b für einen Isolierstoff