

Halbleiter – einige "damals" offene Fragen

Leitfähigkeit steigt mit Temperatur

(Metalle: $\sigma = ne^2\tau/m$, $n=\text{const}$, τ bestimmt σ , fällt wg. e-ph-Streuung)

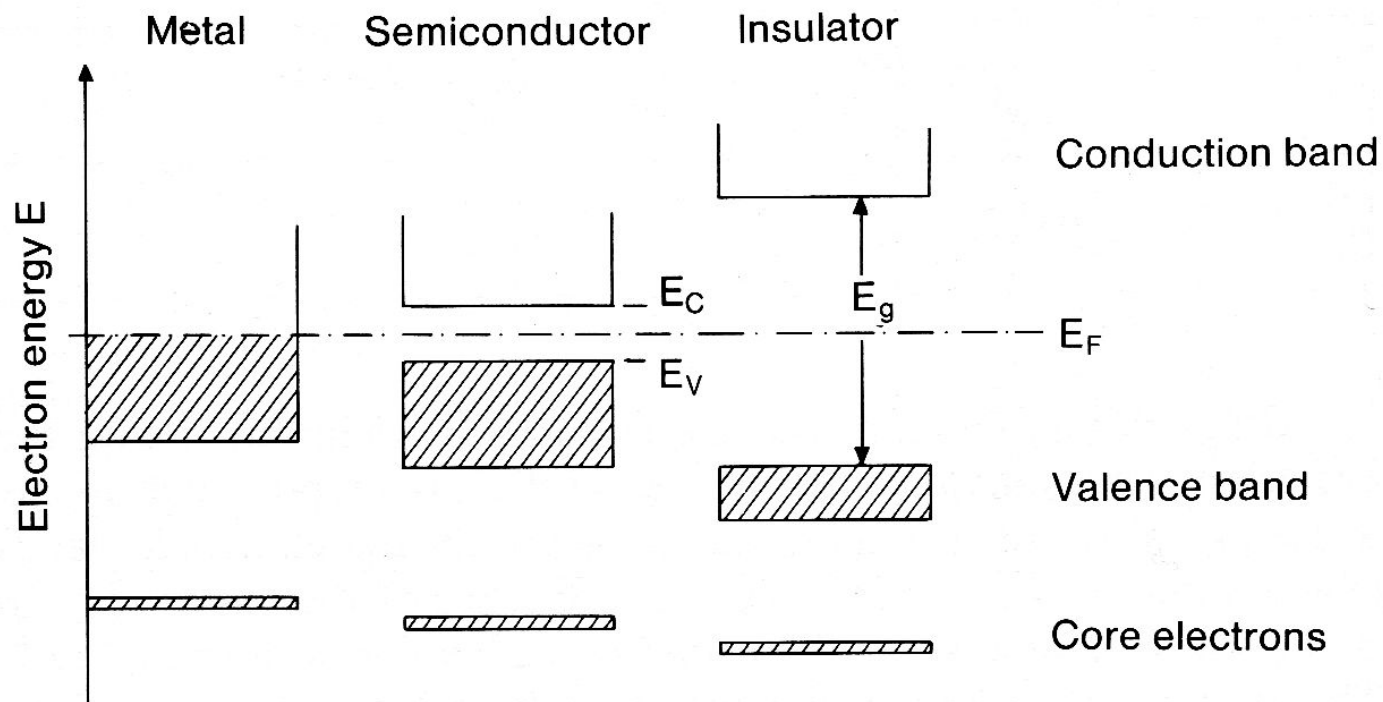
Ursache: $n \sim \exp(-E_A/k_B T)$

extreme Streuung experimenteller Daten

Photoleitung

Gleichrichtung an Halbleiterkontakten

	ρ (Ωcm)
metals	10^{-6}
semiconductors	$10^{-3} \dots 10^9$
insulators	10^{22}

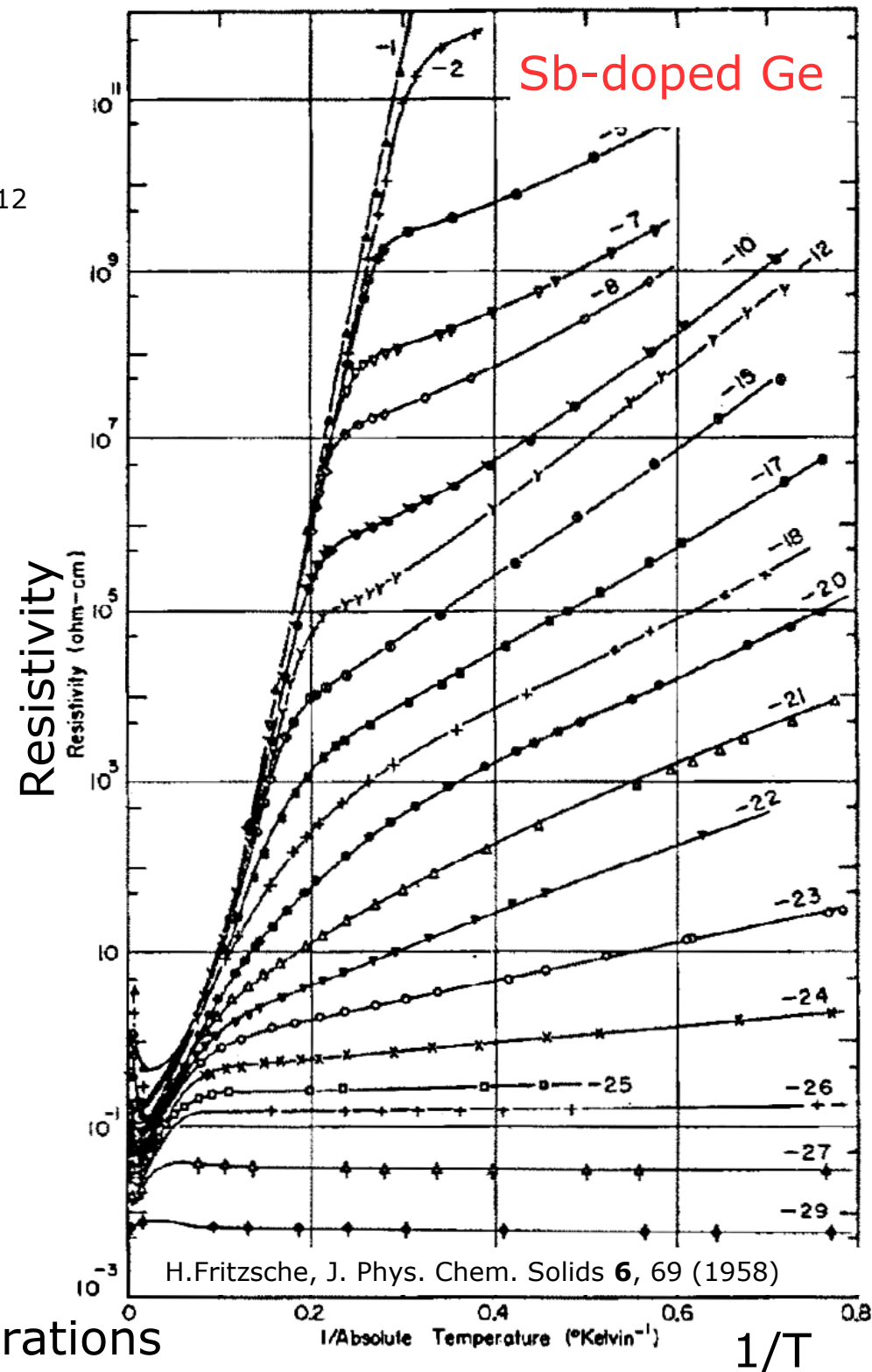


Drastischer Einfluss der Probenreinheit

10^{-8} at% spürbar

10^3 -Änderung der Defektdichte ändert σ um 10^{12}

Sample code number	N_D (cm^{-3})
-1	5.3×10^{14}
-2	9.3×10^{14}
-5	1.6×10^{15}
-7	2.3×10^{15}
-8	3.0×10^{15}
-10	5.2×10^{15}
-12	8.5×10^{15}
-15	1.3×10^{16}
-17	2.4×10^{16}
-18	3.5×10^{16}
-20	4.5×10^{16}
-21	5.5×10^{16}
-22	6.4×10^{16}
-23	7.4×10^{16}
-24	8.4×10^{16}
-25	1.2×10^{17}
-26	1.3×10^{17}
-27	2.7×10^{17}
-29	9.5×10^{17}



Note: these are very low concentrations

Elemente

mit halbleitenden

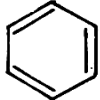
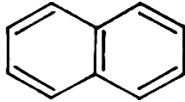
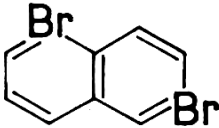
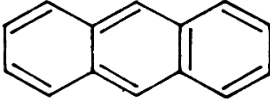
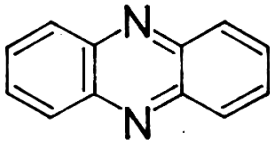
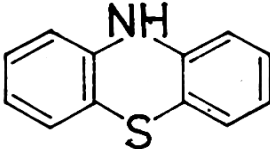
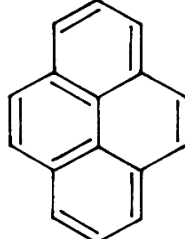
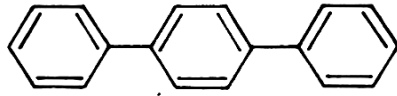
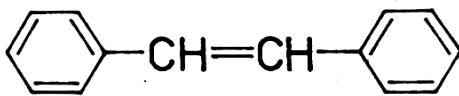
Modifikationen

		-gruppen						Perioden		
		III	IV	V	VI	VII	VIII/0			
								4,0026 He Helium	1	
								2	K-Schale n=1	
		10,811 B 5 Bor	12,01 C 6 Kohlenstoff	14,007 N 7 Stickstoff	15,999 O 8 Sauerstoff	18,998 F 9 Fluor	20,179 Ne 10 Neon	2		
								2	K-Schale n=1	
								2 6	L-Schale 2	
		26,982 Al 13 Aluminium	28,086 Si 14 Silicium	30,974 P 15 Phosphor	32,06 S 16 Schwefel	35,453 Cl 17 Chlor	39,948 Ar 18 Argon	3		
Ia	IIa							2	K-Schale n=1	
								2 6	L-Schale 2	
								2 6	M-Schale 3	
546 Cu Kupfer	65,38 Zn Zink	69,72 Ga Gallium	72,59 Ge Germanium	74,922 As Arsen	78,96 Se Selen	79,904 Br Brom	83,80 Kr Krypton	4		
								2	K-Schale n=1	
								2 6	L-Schale 2	
								2 6 10	M-Schale 3	
								2 6 10	N-Schale 4	
7,87 Ag Silber	112,40 Cd Cadmium	114,82 In Indium	118,69 Sn Zinn	121,75 Sb Antimon	127,60 Te Tellur	126,90 I Jod	131,30 Xe Xenon	5		
								2	K-Schale n=1	
								2 6	L-Schale 2	
								2 6 10	M-Schale 3	
								2 6 10	N-Schale 4	
								2 6 10	O-Schale 5	
196,97 Au Gold	200,59 Hg Quecksilber	204,37 Tl Thallium	207,2 Pb Blei	208,98 Bi Wismut	Po* Polonium	At* Astat	Rn* Radon	6		
								2	K-Schale n=1	

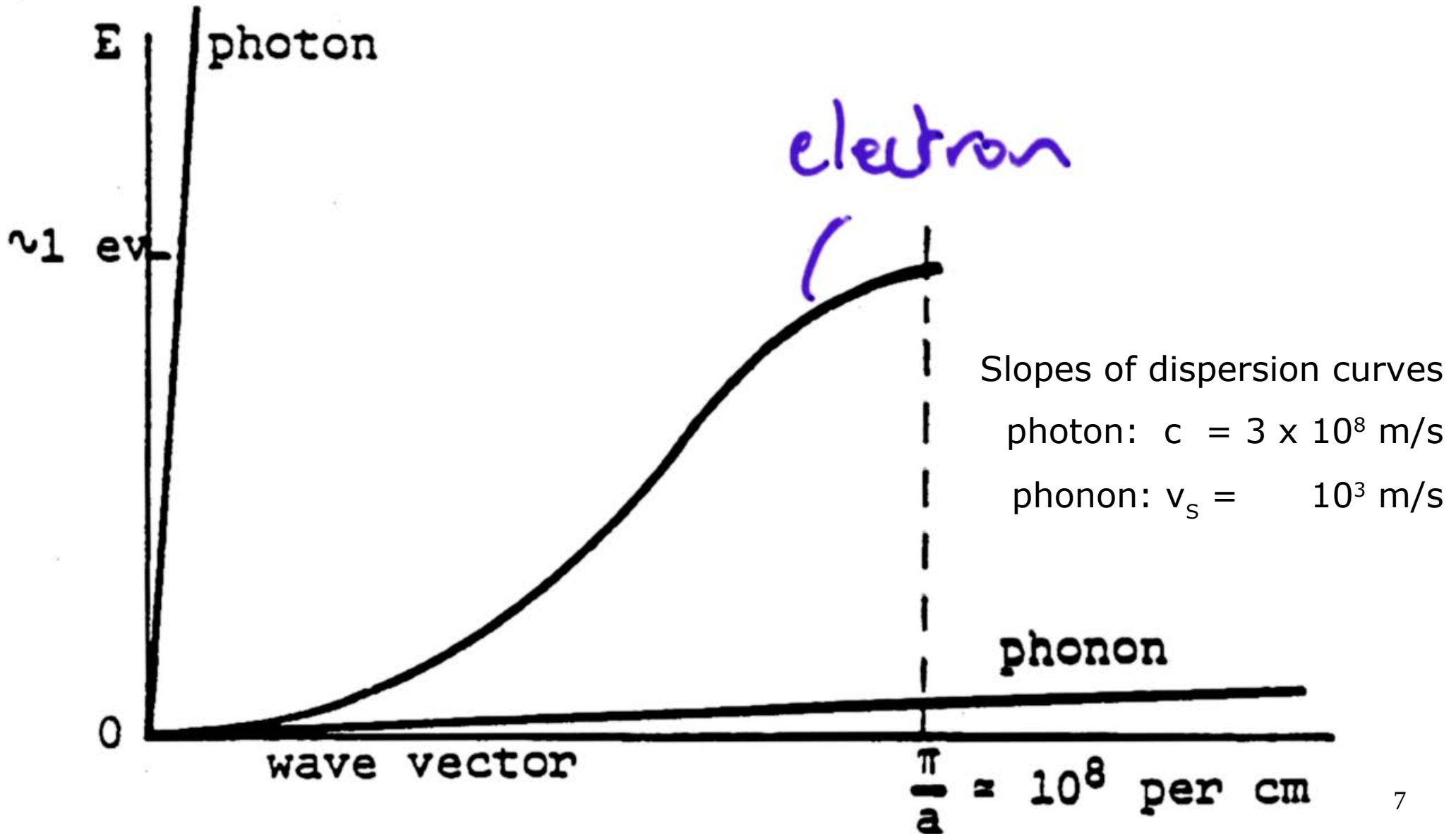
Verbindungshalbleiter

Grad der halbleitenden Verbindungen	Zahl der möglichen Kombinationen	real vorhandene Kombinationen	Beispiele	Beispiel für konkrete halbleitende Verbindungen
binär	21	9	$A^{III}B^V, A^{II}B^{IV}, A^I B^{VII}$ $A_2^{II}B_3^{VI}, A_3^{II}B_3^{VII}, A_2^{III}B^{VI}$	GaAs InSb, CdS
ternär	70	10	$A^I B^{III} C_2^{VI}, A_2^I B^{IV} C_3^{VI}$ $A^{II} B^{IV} C_2^V, A_3^I B^V C_4^{VI}$	CuGaSe ₂
quaternär	105	37	$A_{3y}^I B_{1/2-4y}^{II} C_y^V D_{1/2}^{VI}$	CuGaSe ₂ /GaAs
5komponentig	84	42	$A^{III}B^V / A^I B^{III} C_2^{VI} / A_2^{III} B^{IV} C^{VI}$ $m \quad /n \quad /1-m-n$	—
6komponentig	35	21	$A_{1-x-y-z-u-v} B_x C_y D_z E_u F_v$	—
7komponentig	6	4	$A_{1-x-y-z-u-v-w} B_x C_y D_z E_u F_v G_w$	—

einige
organische
Halbleiter

		$\frac{\mu_n}{\text{cm}^2/\text{V}\cdot\text{s}}$	$\frac{\mu_p}{\text{cm}^2/\text{V}\cdot\text{s}}$
Benzen		1,5	0,2
Naphtalen		0,7	1,4
1,4 - Dibrom - naphtalen		0,03	0,9
Anthracen		2,0	2,0
Phenazin		1,1	—
Phenothiazin		5	0,1
Pyren		—	0,35
p - Terphenyl		—	$3 \cdot 10^{-2}$
Stilben		—	$2 \cdot 10^{-3}$

Photons are an efficient source of energy but not of wave vector, while **phonons** are an efficient source of wave vector and not of energy



momenta:

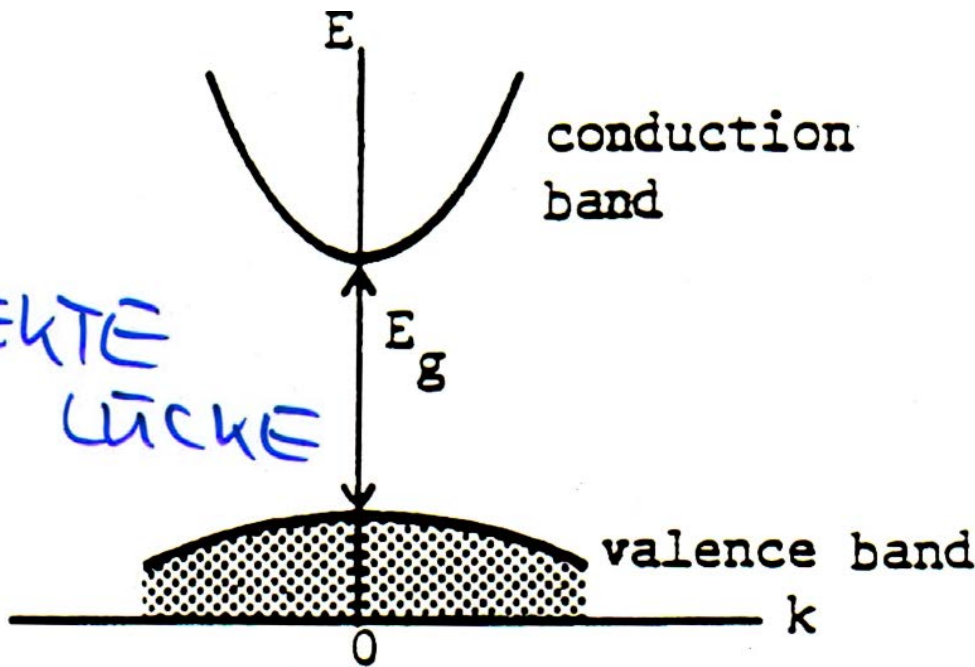
\mathbf{q} photon

\mathbf{Q} phonon

$$\vec{k}' = \vec{k} + \vec{q}$$

$$E(\vec{k}') = E(\vec{k}) + \hbar\omega_{\mathbf{q}}$$

DIREKTE
LÜCKE

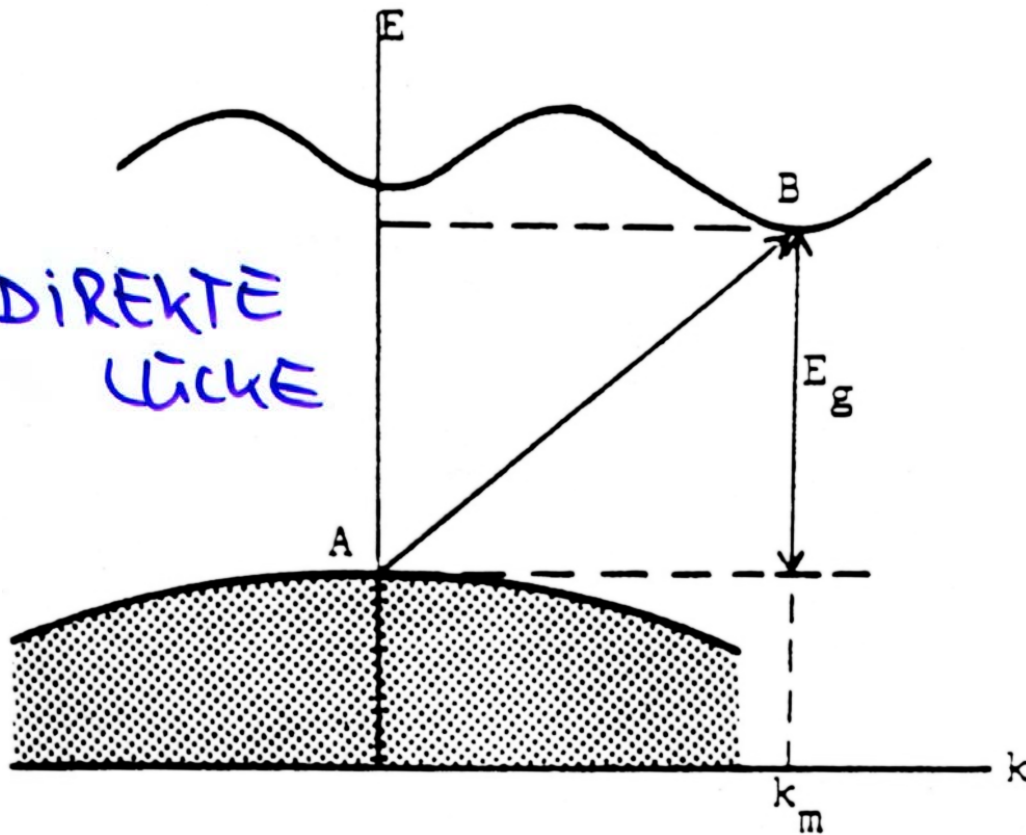


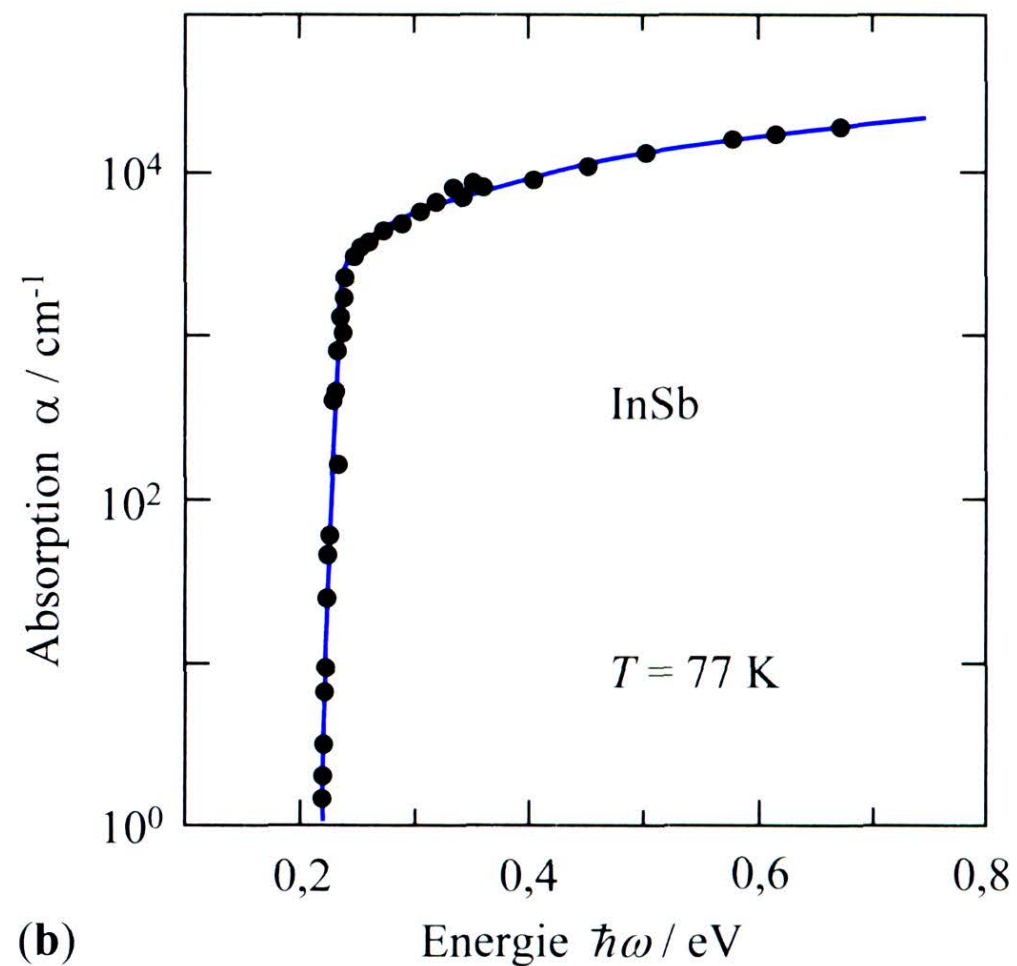
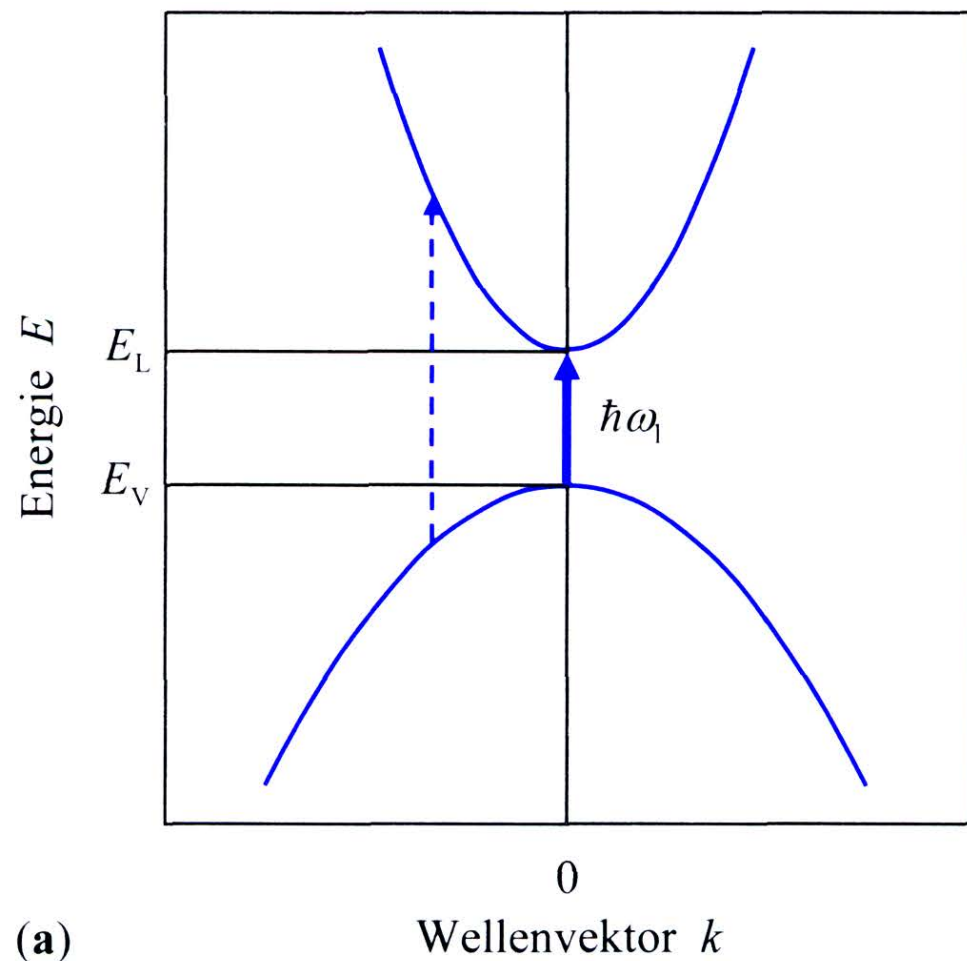
$$\vec{k}' = \vec{k} + \vec{q} + \vec{Q} = \vec{k} + \vec{Q}$$

because we may set $q = 0$

$$\begin{aligned} E(\vec{k}') &= E(\vec{k}) + \hbar\omega_{\mathbf{q}} + \hbar\Omega_{\mathbf{Q}} \\ &= E(\vec{k}) + \hbar\omega_{\mathbf{q}} \text{ because } \hbar\Omega_{\mathbf{Q}} = 0 \end{aligned}$$

INDIREKTE
LÜCKE





Optische Absorption bei direkter Bandlücke

Bild 10.2 Hunklinger

(a) Schema des Absorptionsvorgangs

Dicker Pfeil: Übergang minimaler Energie. Gestrichelter Pfeil: höhere Photonenenergie

(b) Optischer Absorptionskoeffizient von InSb, *logarithmisch*, gegen Photonenenergie

Nach G.W. Gobeli, H.Y. Fan, Phys. Rev. **119**, 613 (1960)

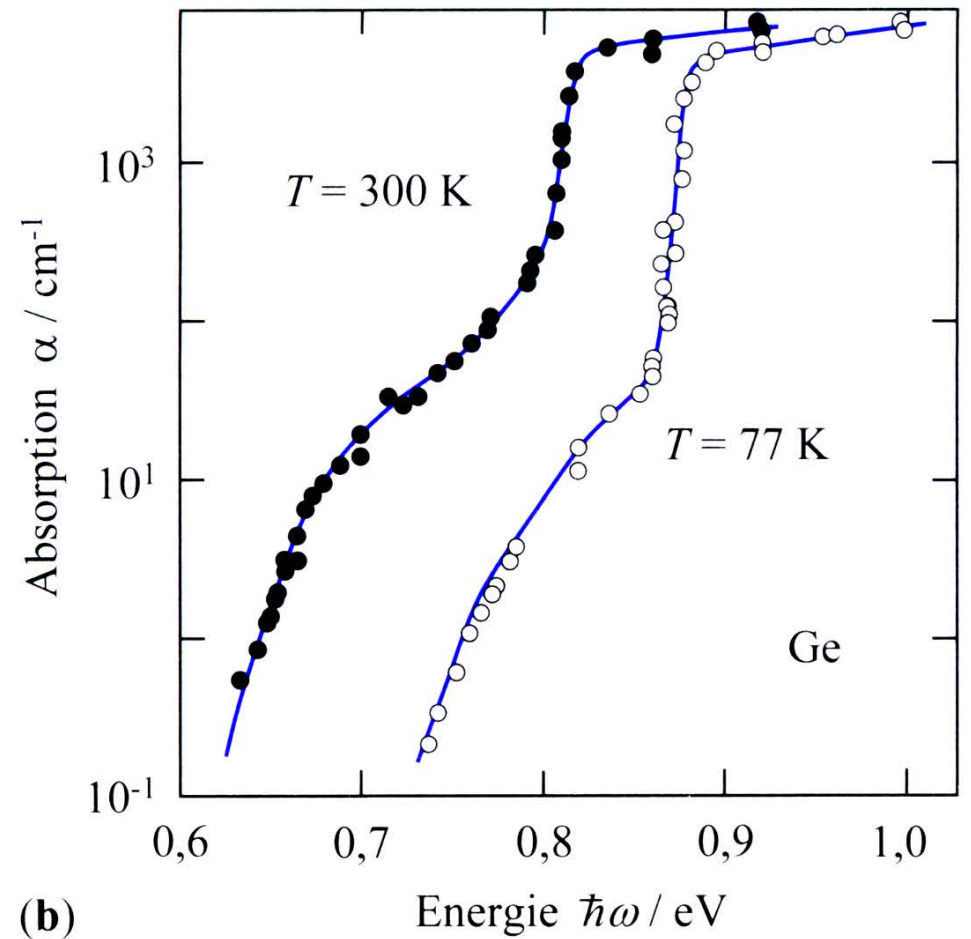
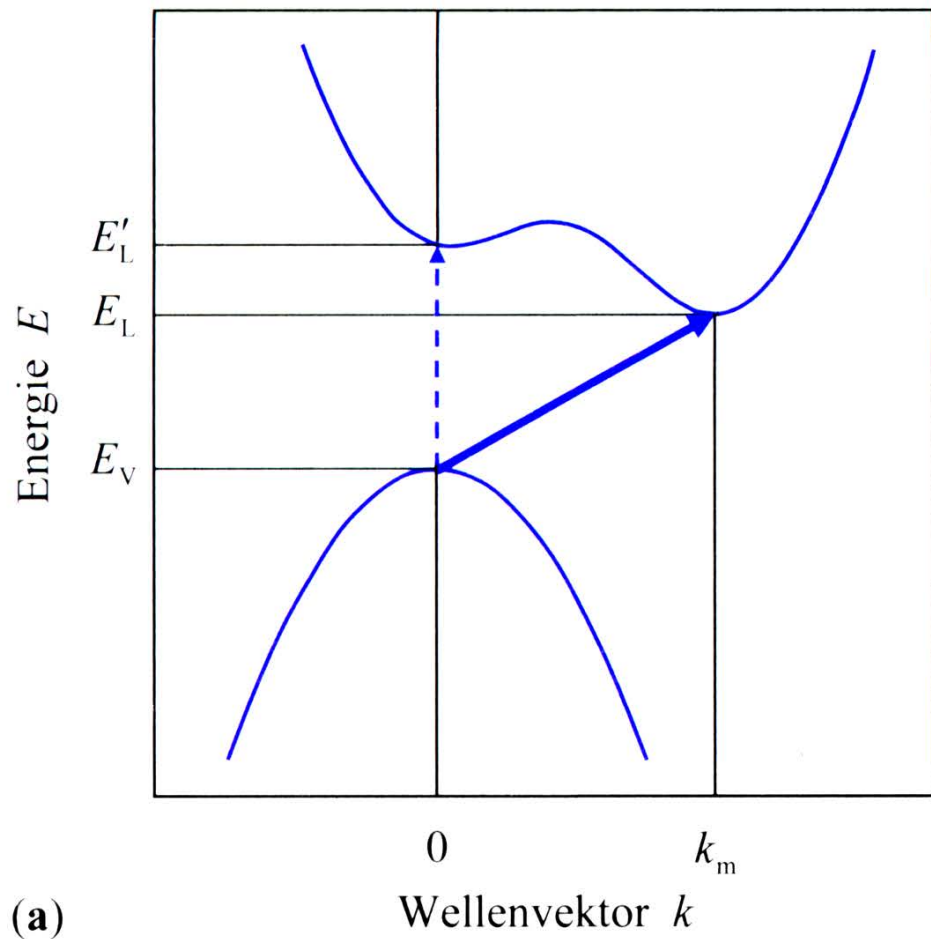


Bild 10.3 Hunklinger **Optische Absorption bei indirekter Bandlücke**

(a) Schema des Prozesses.

E'_L : Energie des Leitungsbandminimums am Γ -Punkt

Übergang minimaler Energie (durchgezogener Pfeil) erfordert das Mitwirken eines Phonons.

Der direkte Übergang kleinster Energie ist gestrichelt gezeichnet.

(b) Absorptionskoeffizient von Ge, logarithmisch, gegen Photonenenergie.

Tabelle 8.1: Energielücke zwischen Valenz- und Leitungsband.

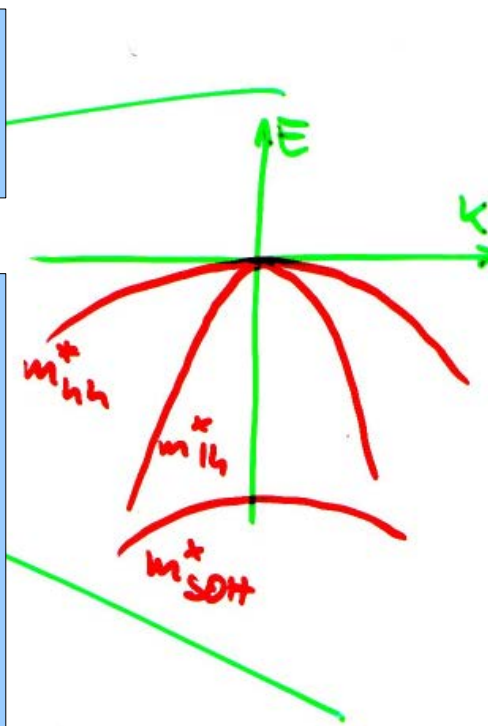
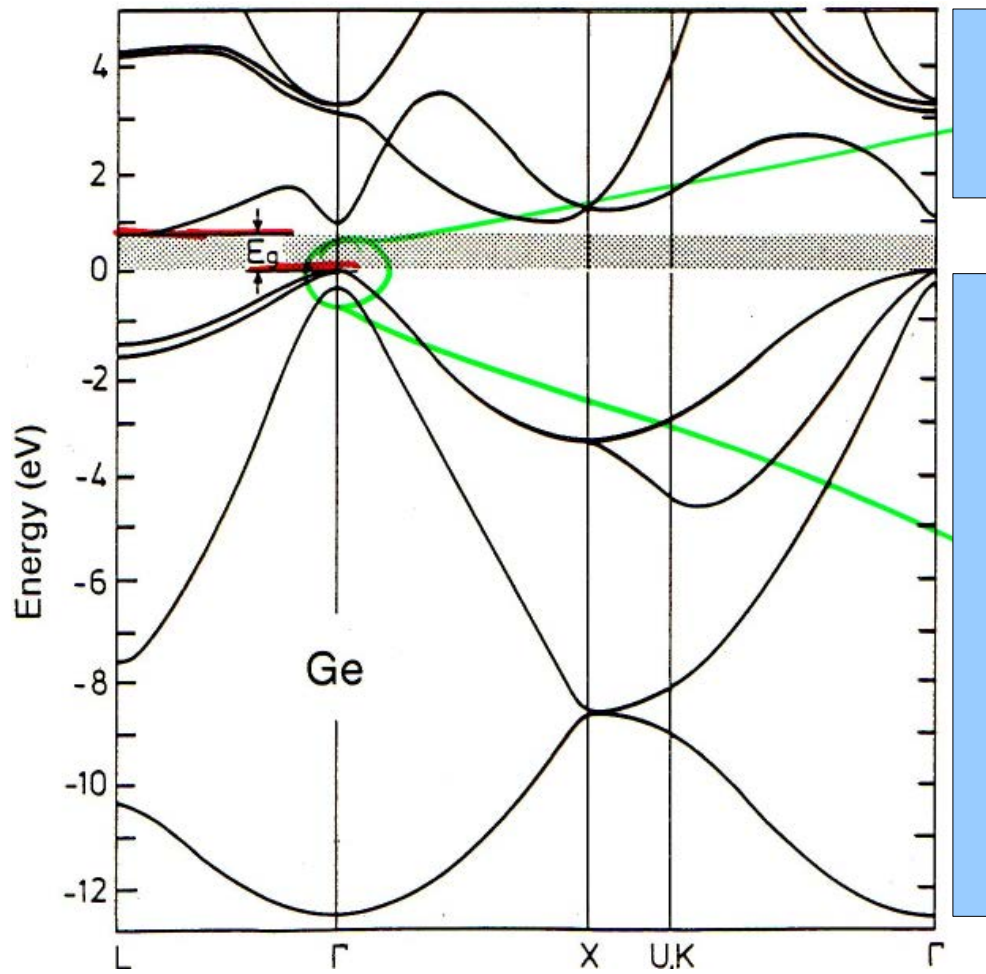
(i = indirekte Lücke, d = direkte Lücke)

Kristall	Lücke	E_g, eV		Kristall	Lücke	E_g, eV	
		0 K	300 K			0 K	300 K
Diamant	i	5,4		SiC (hex)	i	3,0	–
Si	i	1,17	1,11	Te	d	0,33	–
Ge	i	0,744	0,66	HgTe ^a	d	–0,30	
α Sn	d	0,00	0,00	PbS	d	0,286	0,34–0,37
InSb	d	0,23	0,17	PbSe	i	0,165	0,27
InAs	d	0,43	0,36	PbTe	i	0,190	0,29
InP	d	1,42	1,27	CdS	d	2,582	2,42
GaP	i	2,32	2,25	CdSe	d	1,840	1,74
GaAs	d	1,52	1,43	CdTe	d	1,607	1,44
GaSb	d	0,81	0,68	SnTe	d	0,3	0,18
AlSb	i	1,65	1,6	Cu ₂ O	d	2,172	–

^a HgTe ist ein Halbmetall, die Bänder überlappen.

(1) Detektor / Emitter

(2) $E_G = E_G(T)$, warum?



E_{SO}/meV

Si	Ge
~ 290	~ 44

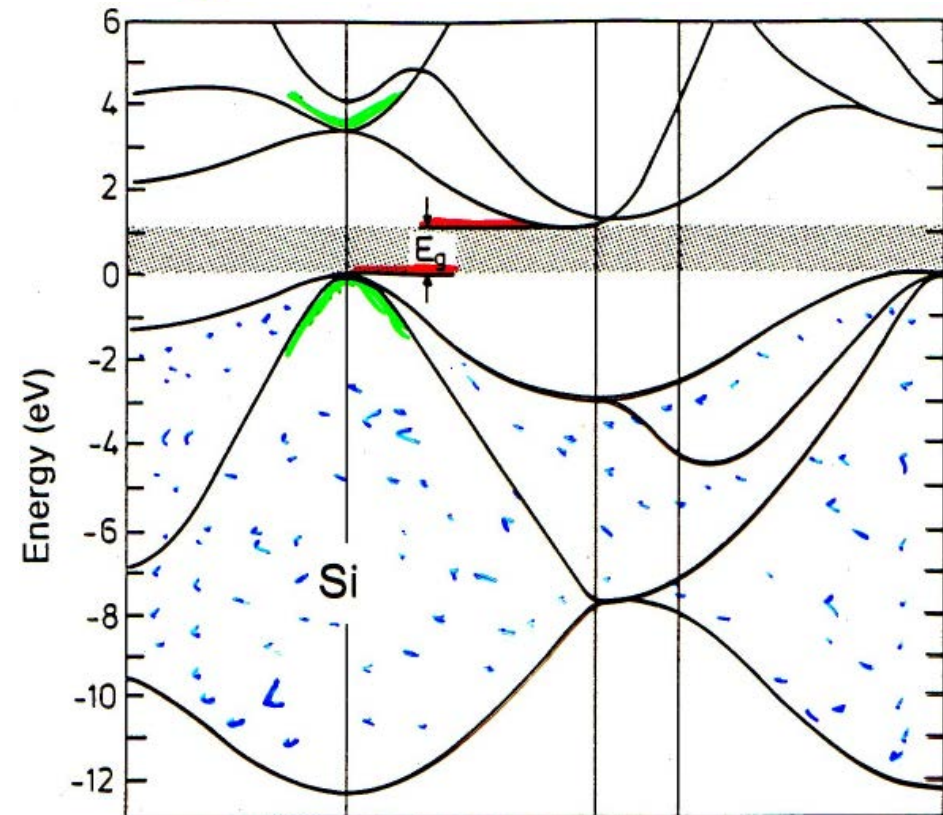


Fig. 12.2. Calculated bandstructures of silicon and germanium. For germanium the spin-orbit splitting is also taken into account. (After [12.1]). Both semiconductors are so-called indirect semiconductors, i.e. the maximum of the valence band and the minimum of the conduction band are at different positions in the Brillouin zone. The minimum of the conduction band of silicon lies along the $\Gamma X = [100]$ direction and that of germanium along the $\Gamma L = [111]$ direction. Note that the form of the Ge bands is very similar to that of Fig. 7.13, although the calculations were performed differently

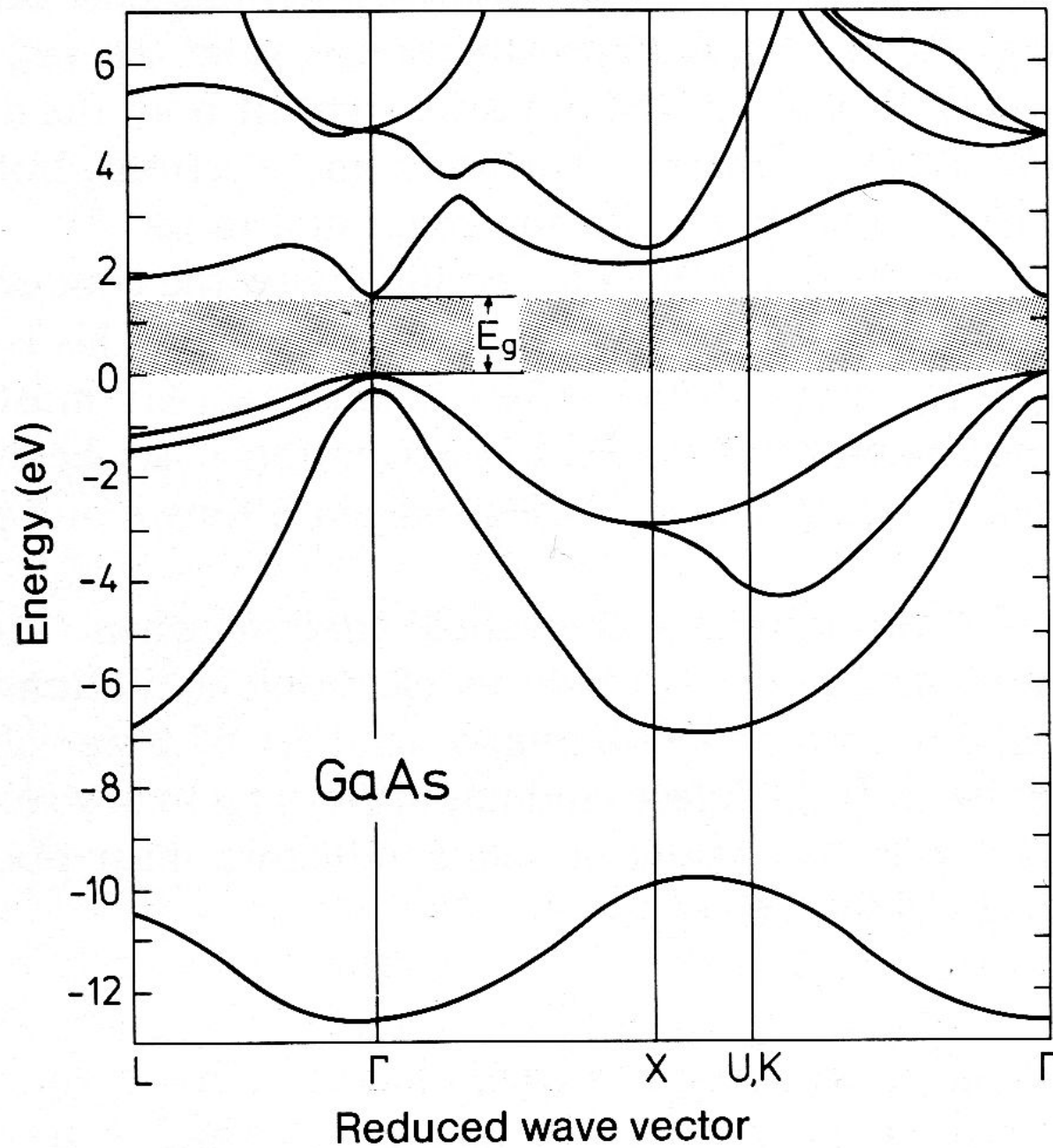


Fig. 12.4. Typical bandstructure of a III-V semiconductor, in this case GaAs. (After [12.1])

Effektive-Masse-Näherung

$E(\mathbf{k})$ ist ziemlich komplex, außer an den Bandextrema,
dort $E(k) \approx ak^2$, d.h.: $m^*(k) \approx \text{const.}$

Ladungsträgerdichten bestimmt durch Bandkanten
parabolische Bandstruktur mit m^* reicht für vieles! (Aber nicht alles; PSC)

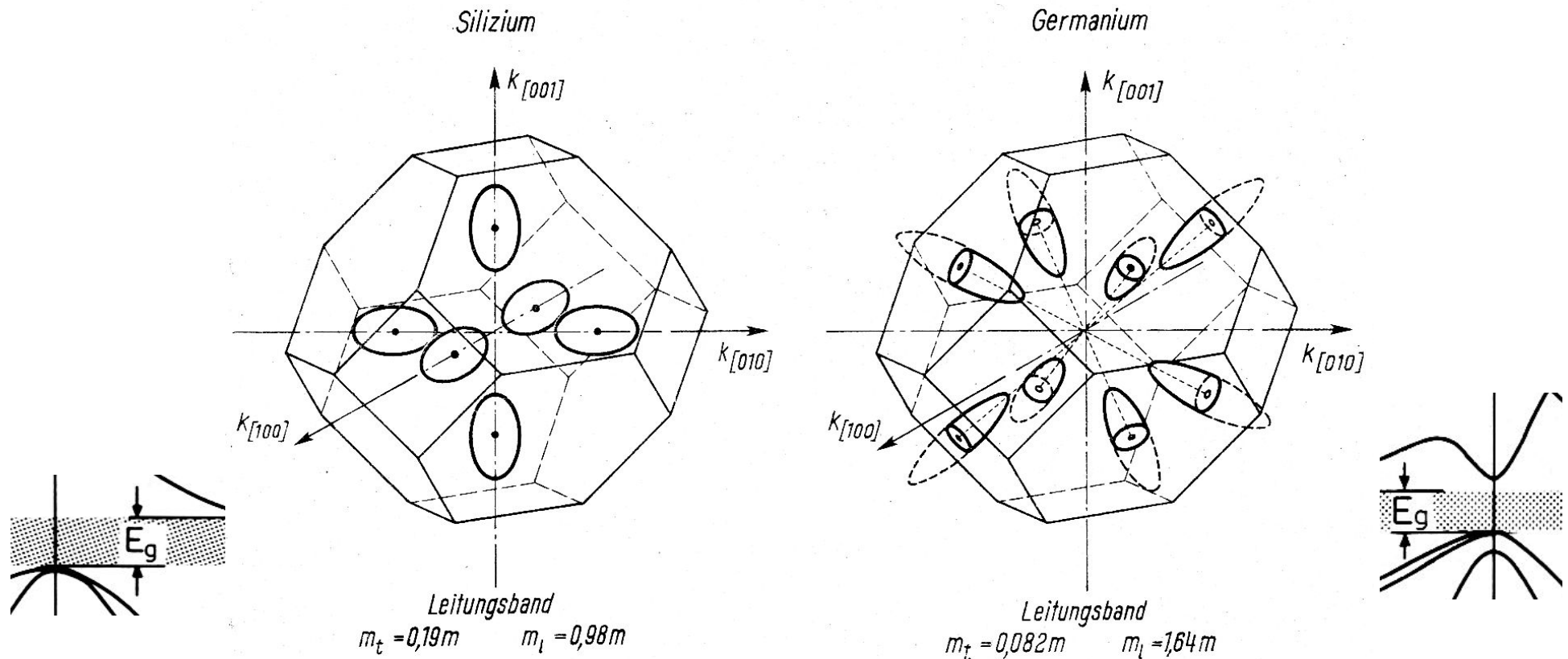


Fig. 131: Flächen konstanter Energie für Leitungselektronen in Silizium und Germanium

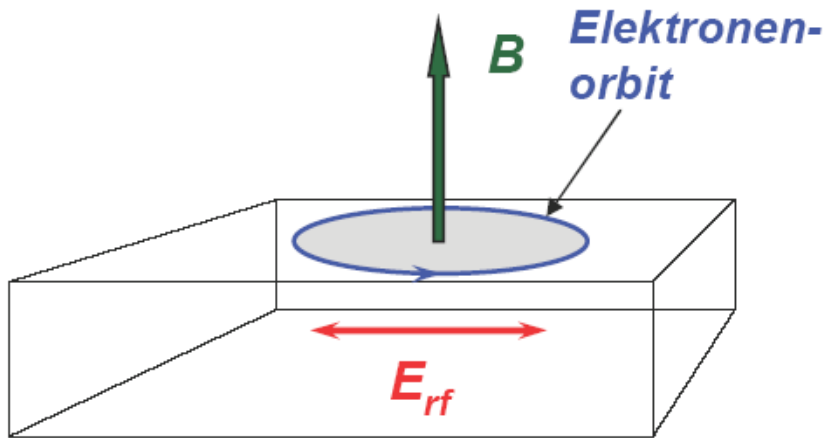
Zyklotronresonanz

Hochfrequenzfeld E_{rf} (24 GHz)

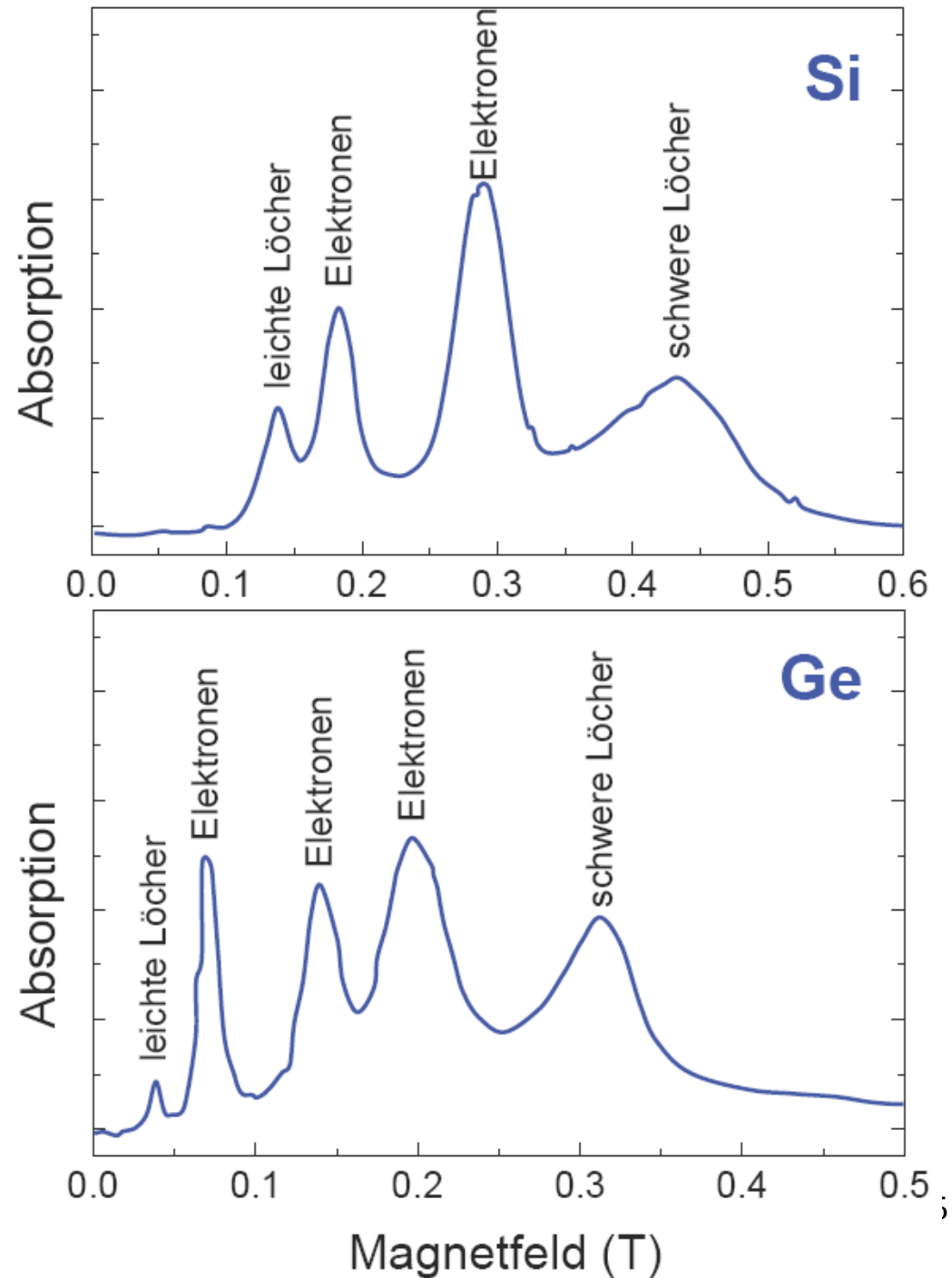
statisches Magnetfeld B

$T = 4$ K, reine Proben

G. Dresselhaus et al., Phys. Rev. 98, 368 (1955)



$$m_c = \left(\frac{\det m^*}{m_{zz}} \right)^{1/2}$$



Quantitatives ...

	ϵ	E_G (eV)@RT	Art der Lücke	m_n/m_e	m_p/m_e	n_i (cm ⁻³)
Ge	16	0,67	i	1,6	0,04 0,28	$2,4 \times 10^{13}$
Si	11,9	1,1	i	0,98	0,16 0,49	$1,5 \times 10^{10}$
GaAs	13,1	1,43	d	0,067	0,082	5×10^7

Konsequenzen? (optoelo, GHz)

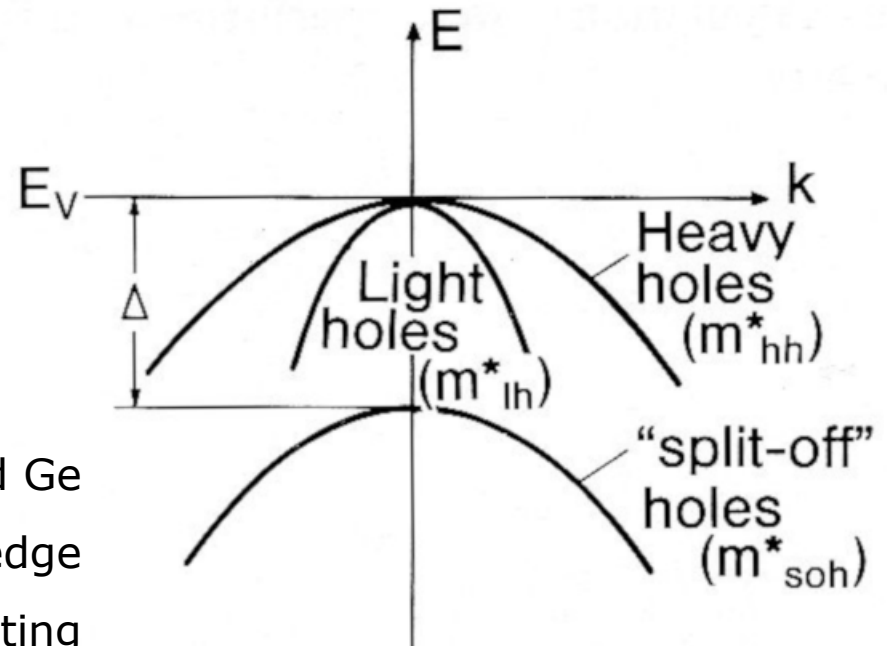


Fig. 12.3 Schematic bandstructure of Si and Ge near the valence band edge
 Δ : spin-orbit splitting

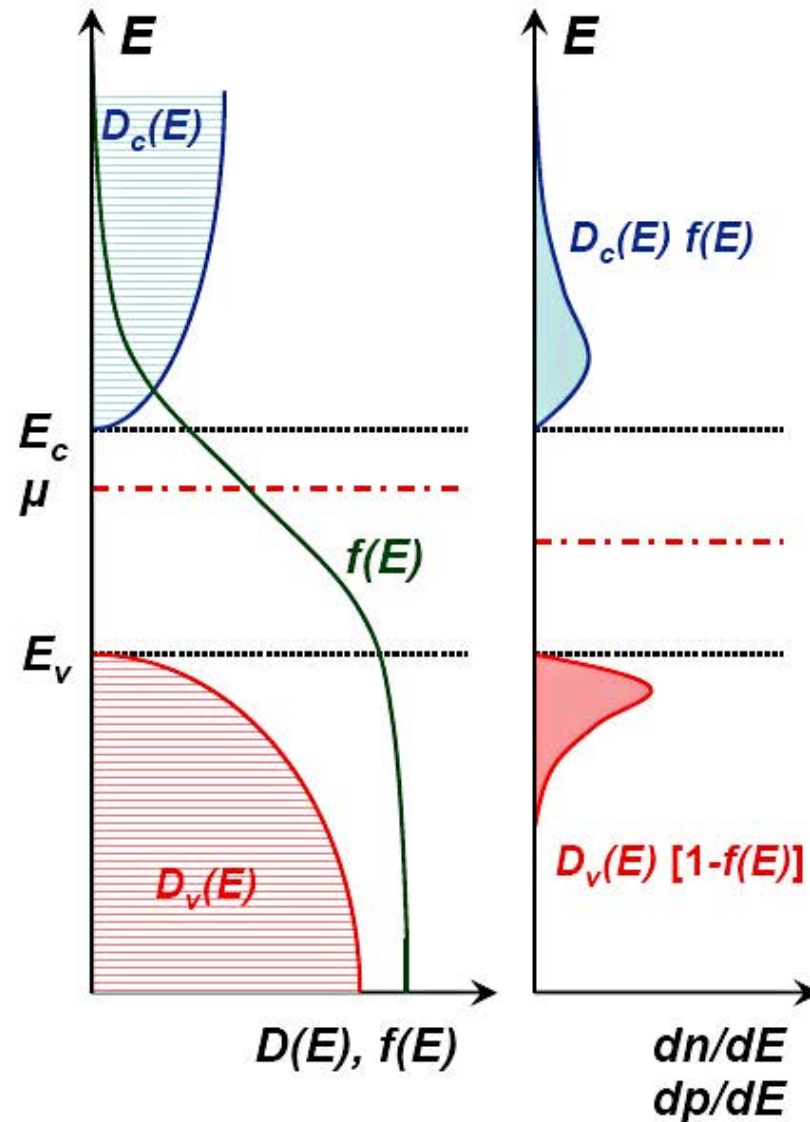
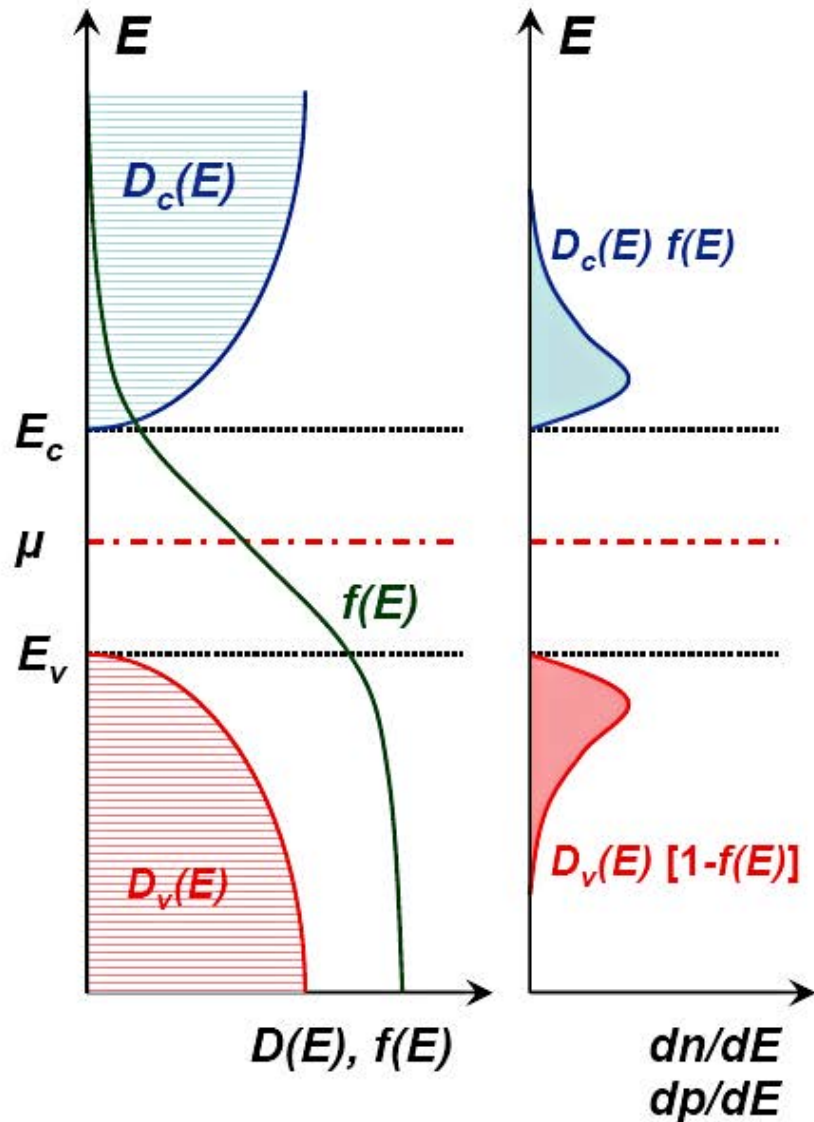
Intrinsischer Halbleiter - Ladungsträgerstatistik

Gegeben E_G , m_p^* , m_n^* , wo liegt μ (E_F)?

(T stark übertrieben)

$$D_v = D_c$$

$$D_v \neq D_c$$



Fermi function $f(E)$, density of states $D(E)$, electron (n) and hole (p) concentrations in the conduction and valence bands assuming that the densities of states in the conduction and valence bands are equal (left) or different (right). The numbers of holes and electrons being identical, E_F is located in / off from the middle of the gap. Its position is T dependent in the latter case.

Tafel

Fraction of e^- in conduction band

$$x \approx \exp(-E_G/2k_B T); \quad k_B T \approx 25 \text{ meV @ } 300 \text{ K}$$

E_G (eV)	x	
4	10^{-35}	\approx zero
1	10^{-9}	"few"
0.25	10^{-2}	"many"

Boltzmann approximation is excellent at RT for $E_G \approx 1 \text{ eV}$

(width of Fermi edge $\ll E_G$)

$$\sigma = |e| (n \mu_n + p \mu_p)$$

Intrinsic conductivity σ is extremely low at these conditions

Gibt es intrinsische Halbleiter?

Minimale Defektdichte ca. 10^{12} cm^{-3} (vgl. atomare Dichte)

n_i bei 300 K:	Ge	$2,4 \cdot 10^{12} \text{ cm}^{-3}$	intrinsisch
	Si	$1,5 \cdot 10^{10} \text{ cm}^{-3}$	extrinsisch

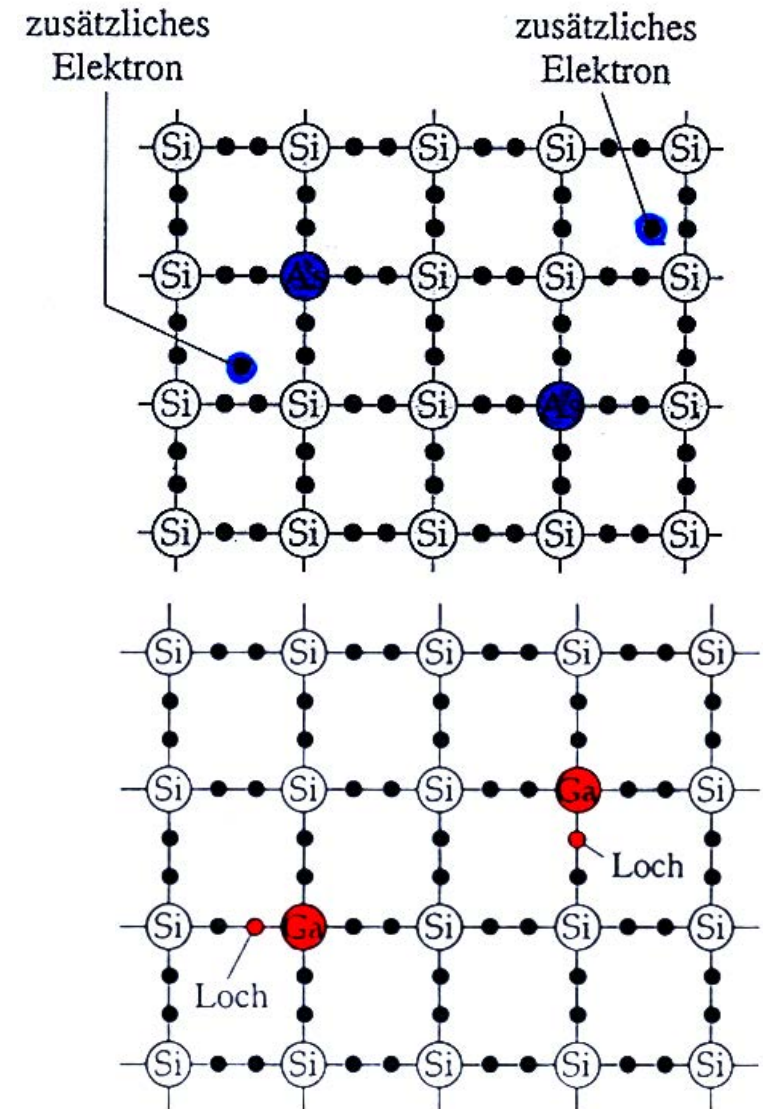
Dotierung

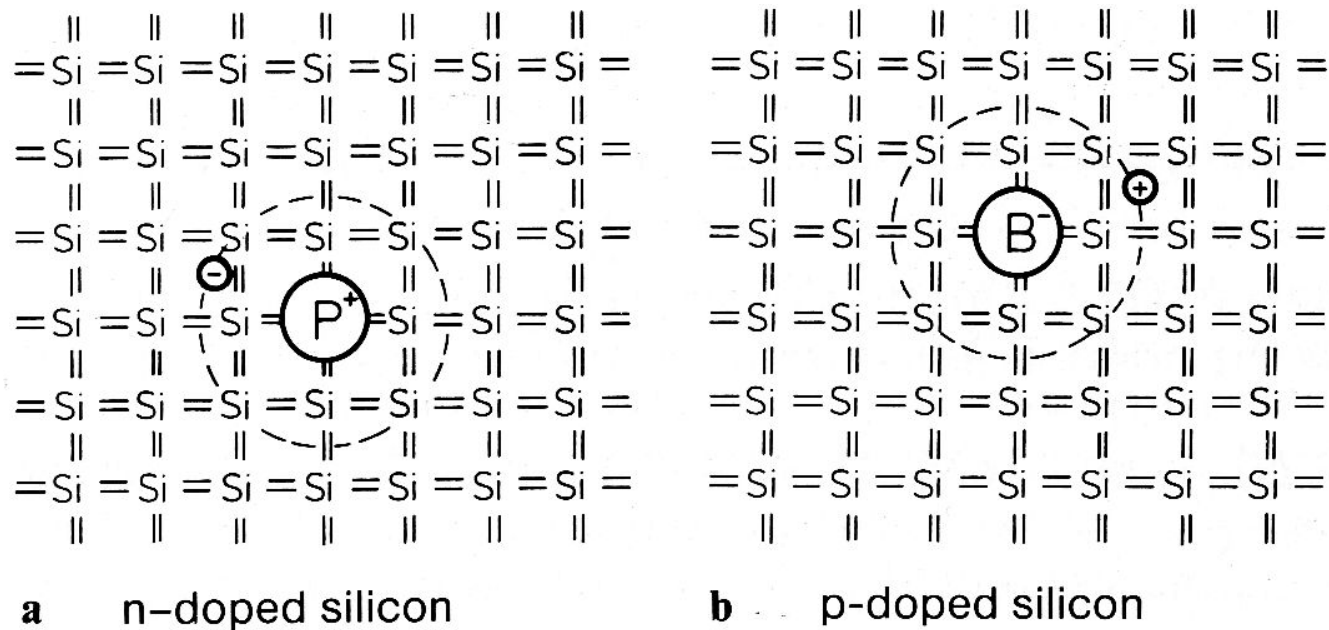
z. B.: Gruppe IV Halbleiter + Spuren von 3- oder 5-wertige Fremdatome

(n.b.: andere Defekte, Selbstkompensation)

5-wertig: P, As, Sb s^2p^3
T=0: 5 Elektronen
T>0: ionisiert
Rumpf⁺ verliert e⁻
Donator

3-wertig: B, Ga, Al, In sp^3
T=0: 3 Elektronen
T>0: ionisiert
Rumpf bindet h⁺ schwach
Akzeptor





Donator (a) bzw. Akzeptor (b) in einem Si-Gitter

Abb. 12.6 Ibach-Lüth

Substitutionelles, fünfwertiges Phosphoratom hat schwach gebundenes Elektron.

Dreiwertiges Bor nimmt zusätzliches auf und erzeugt so schwach gebundenes Loch.

Wasserstoffmodell

$$E_n = -\frac{1}{(4\pi\epsilon_0\epsilon_R)^2} \frac{m^* e^4}{2\hbar^2} \frac{1}{n^2}$$

$$\epsilon_R \sim 10, m^* \sim 0.1m_e \quad 22$$

Why ϵ_R ?

Gitterabstand und Ausdehnung des Störzentrums nicht maßstabgetreu:
Radius der 1. Bohrschen "Störstellenbahn" ca. 10 x Gitterabstand

Donors provide extra electrons in CB

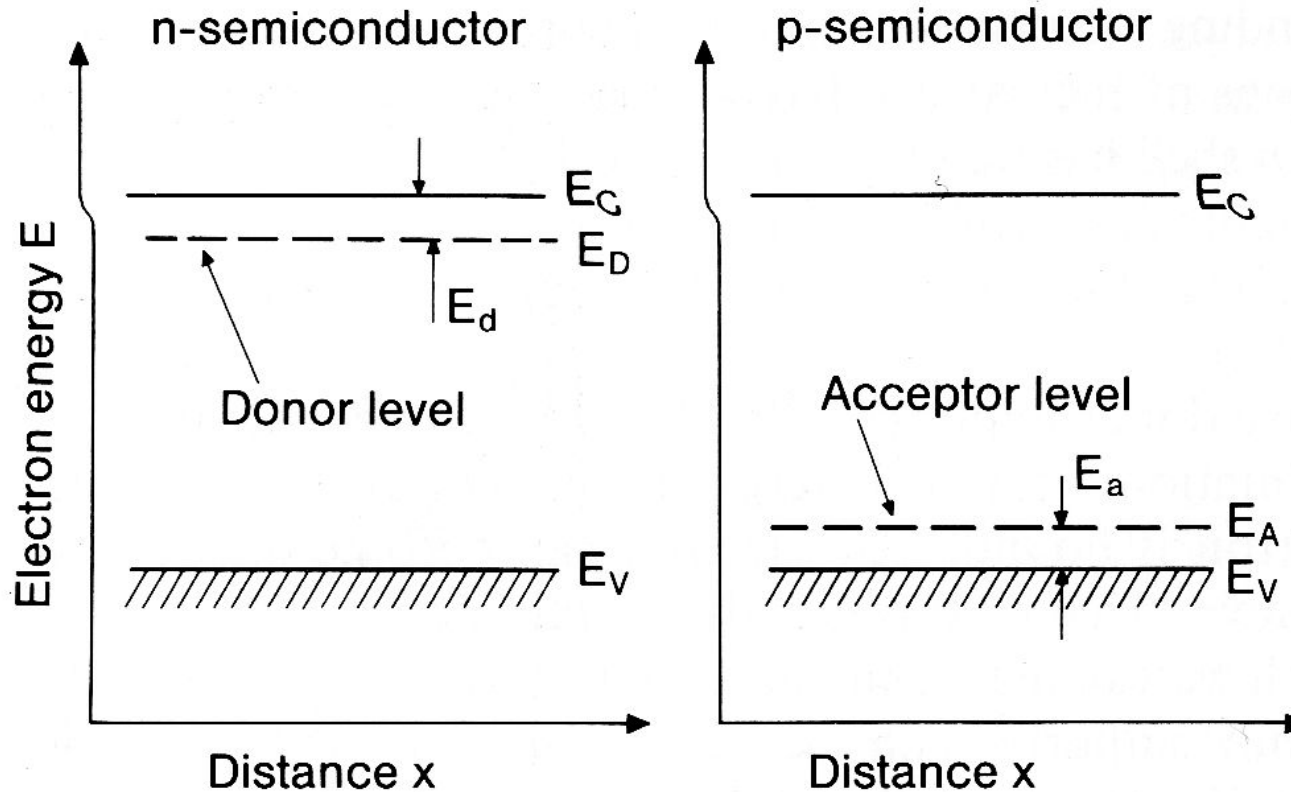
$$\Rightarrow n - p = \Delta n \neq 0$$

Δn depends on donor & acceptor densities

\Rightarrow n-type, p-type semiconductor

Donator- und Akzeptorniveaus (E_d , E_a)

(meV)	Donatoren			Akzeptoren			
	P	As	Sb	B	Al	Ga	In
Si	45	49	39	45	57	65	16
Ge	12	12.7	9.6	10.4	10.2	10.8	11.2



IR absorption of Sb donors in Ge

Fig. 12.8 Ibach Lüth

