

# The physics of particle detectors - Fermi energy -

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# Fermi-Dirac distribution

Semiconductor materials: crystalline lattice

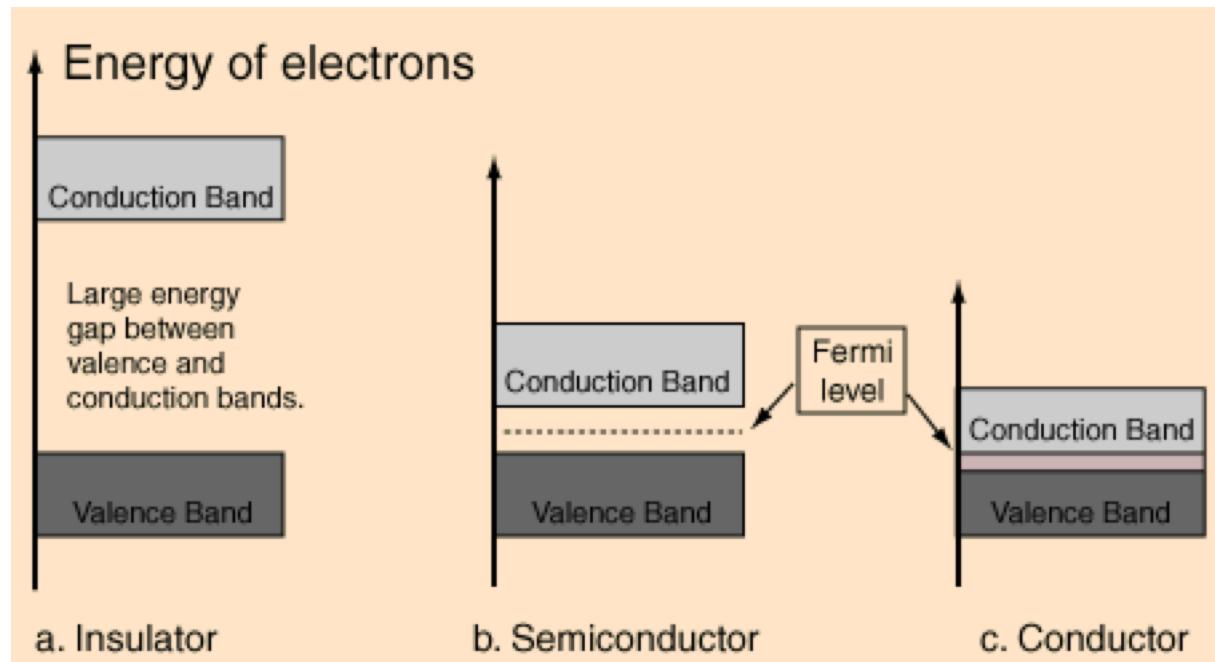
Electrons are fermions → Pauli exclusion principle

Probability distribution:

$$f(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

# Band theory of solids

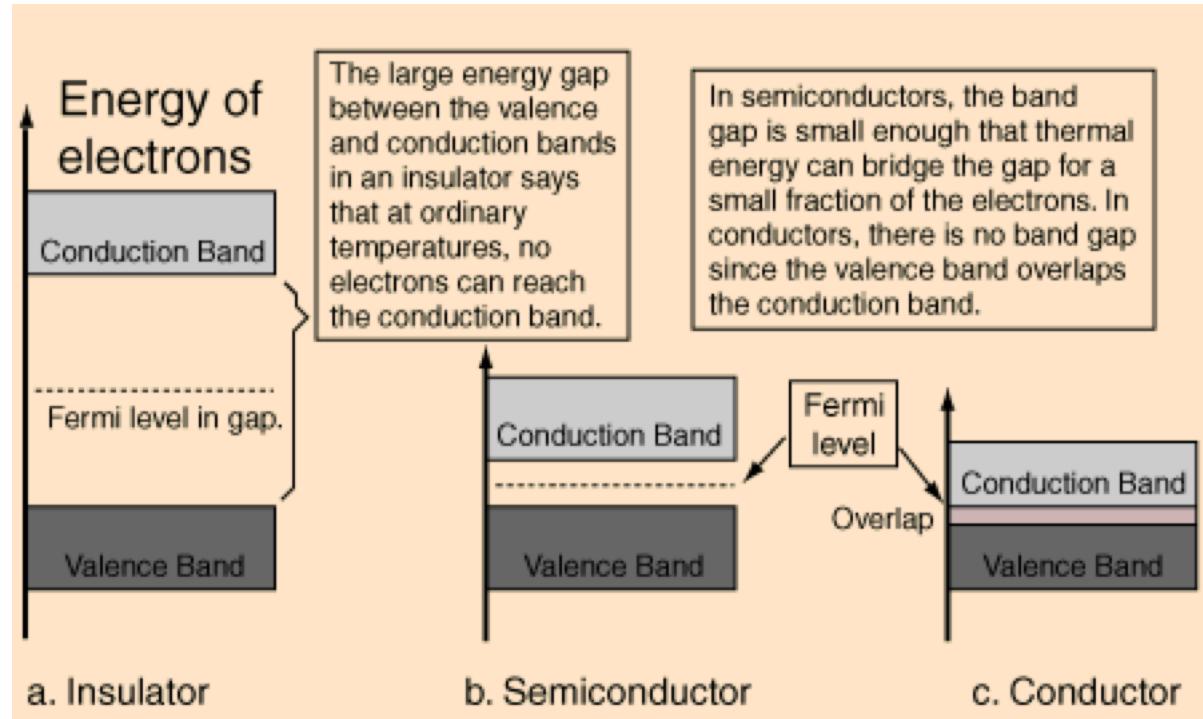
Bands of energy levels are determined by the inter-atomic spacing:



Bands determine the density of available energy states

# Band theory of solids

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# Fermi energy

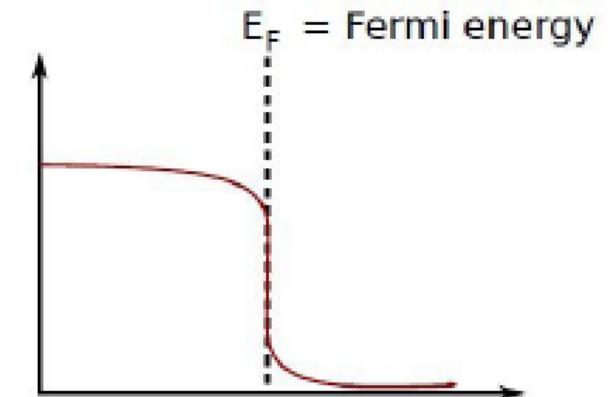
Intrinsic semiconductor,  
Low temperature

Probability distribution from  
Fermi-Dirac statistics

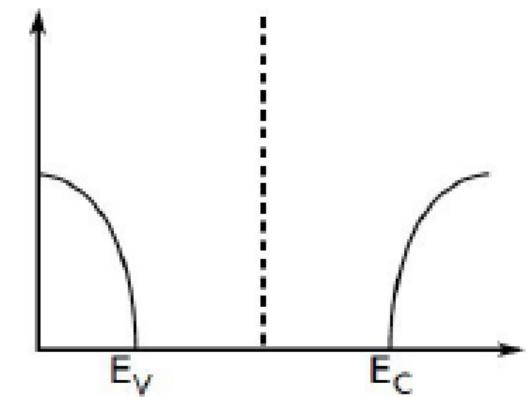
Density of available energy  
states

Resulting distribution of  
charge carriers

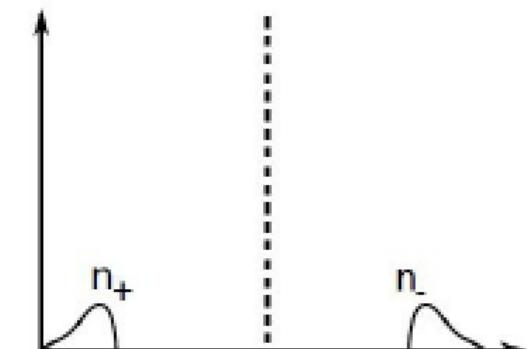
Fermi distribution



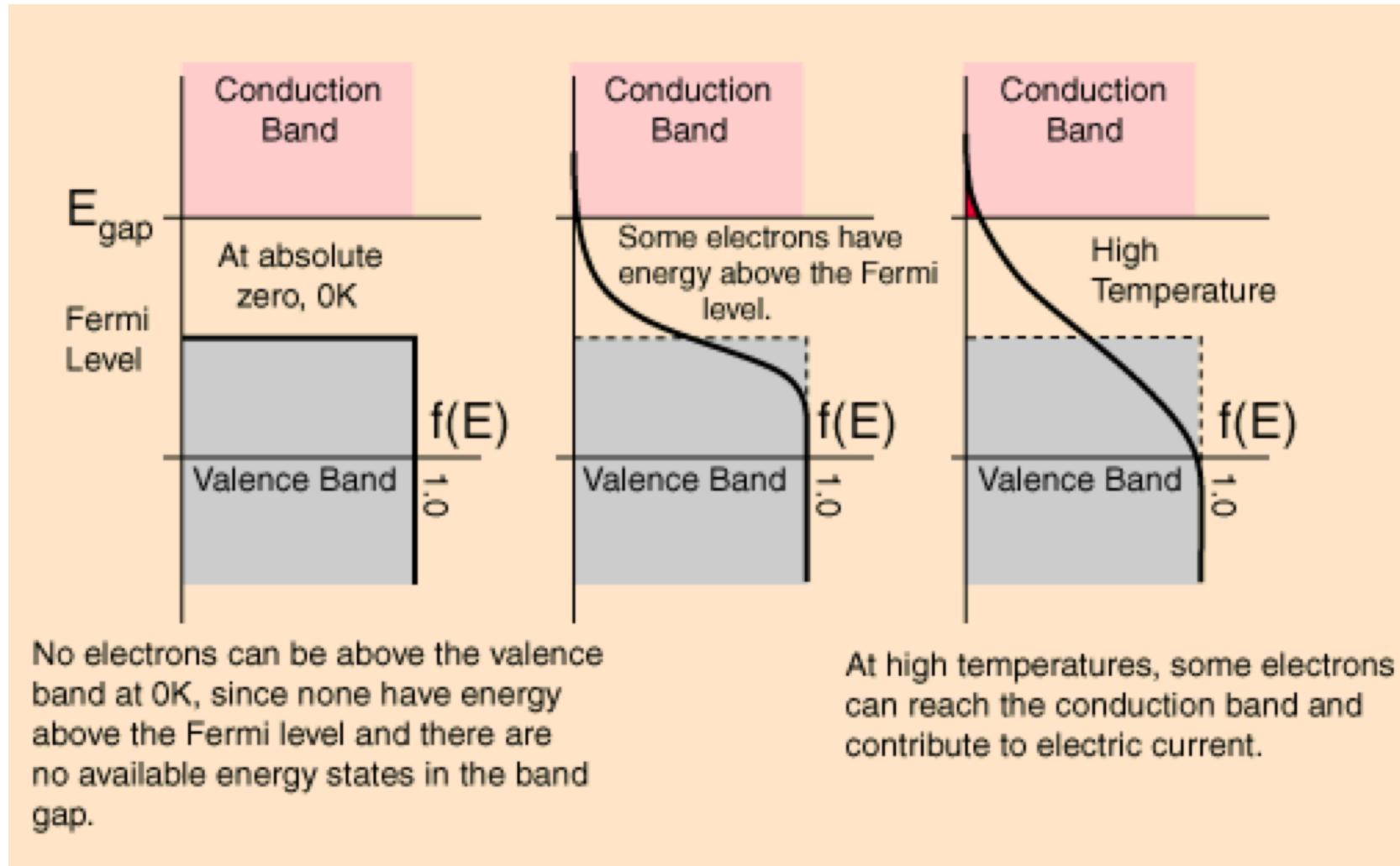
phase space  
density  $g(E)$



charge carrier  
distribution

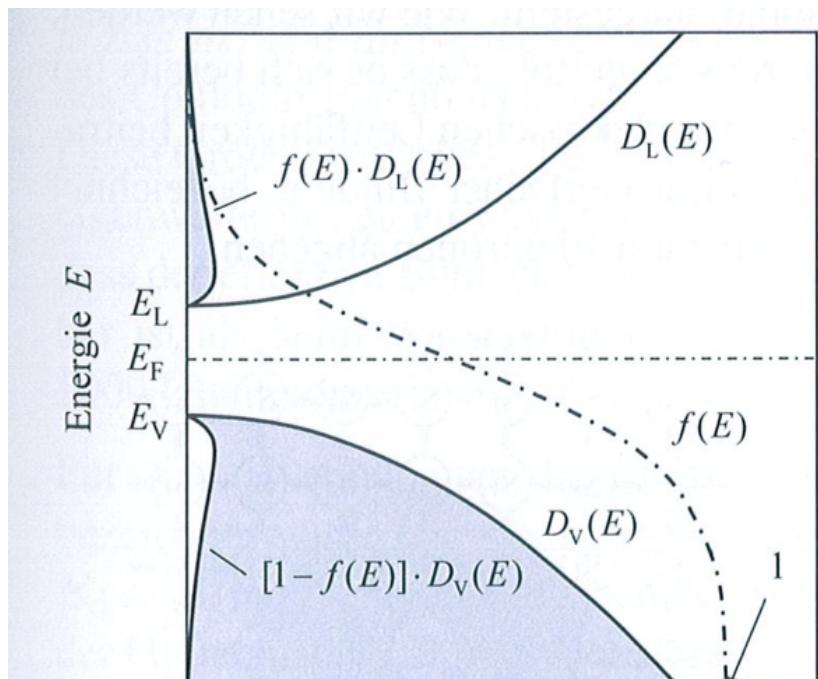


# Semiconductors and Fermi level

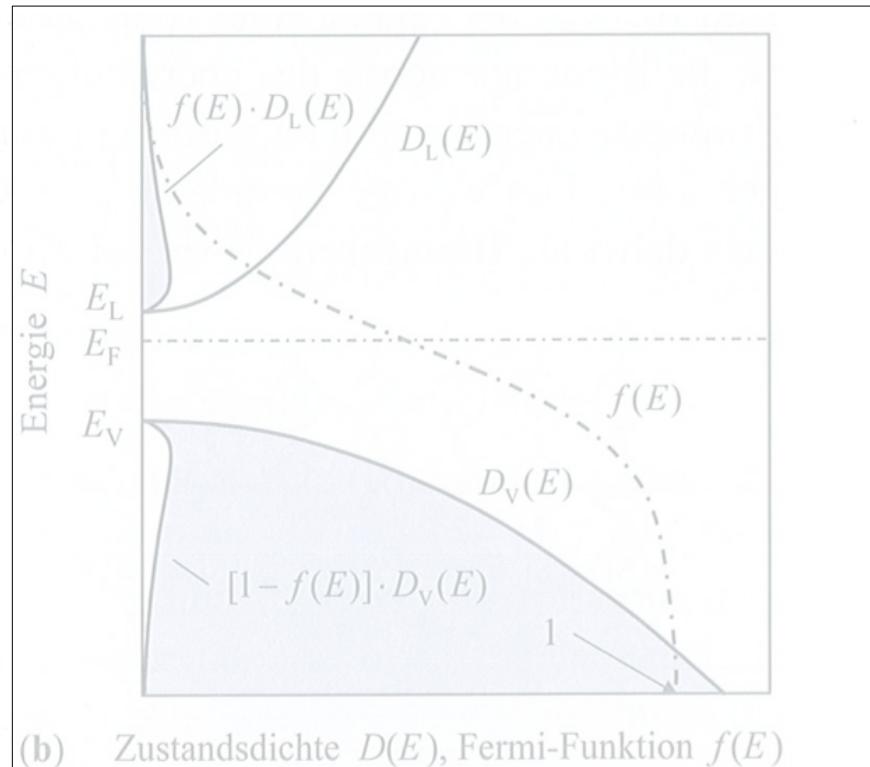


# Semiconductors and Fermi level

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(a) Zustandsdichte  $D(E)$ , Fermi-Funktion  $f(E)$

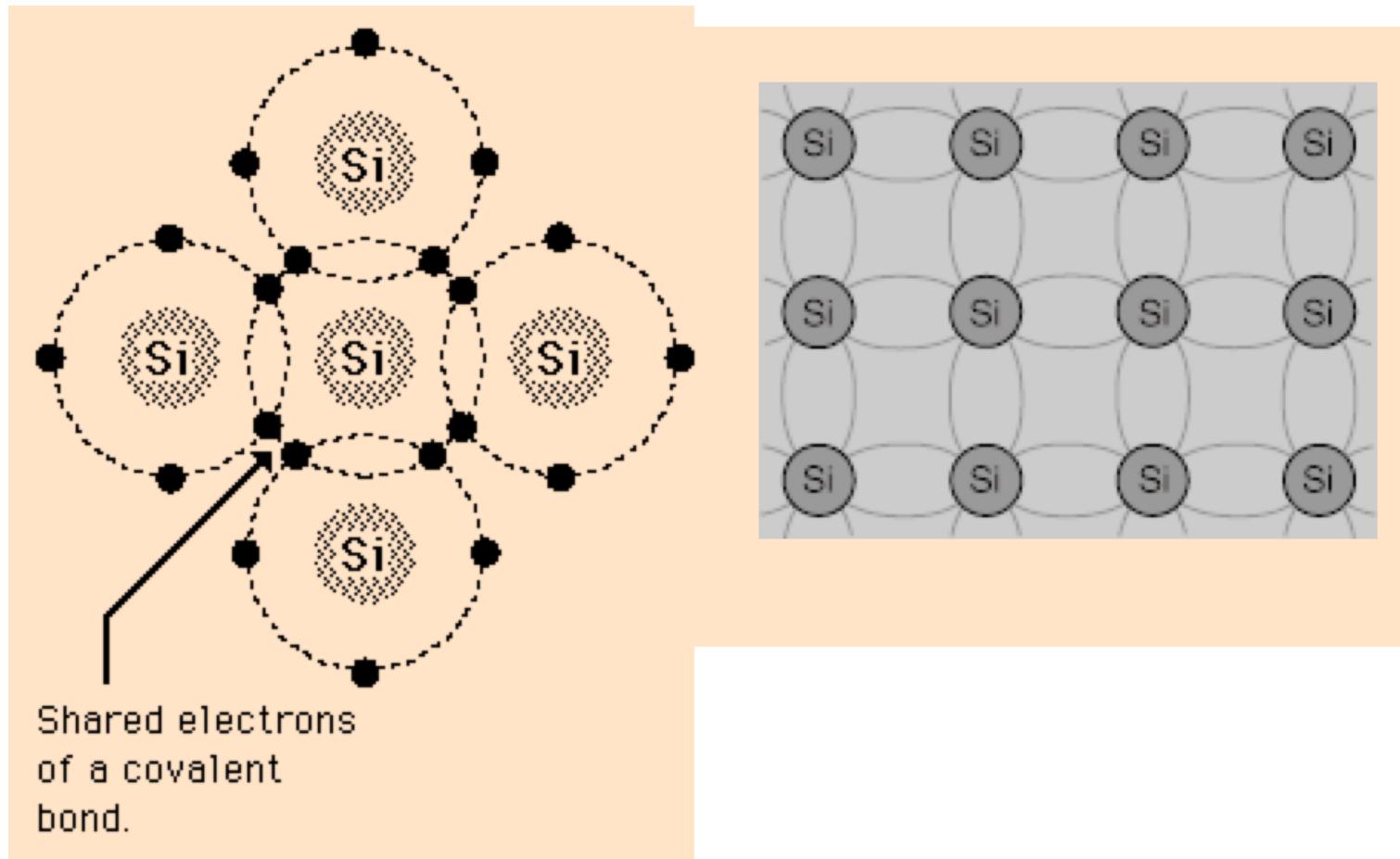


(b) Zustandsdichte  $D(E)$ , Fermi-Funktion  $f(E)$

**Bild 10.6:** Zustandsdichten  $D(E)$  und Fermi-Funktion  $f(E)$  im Valenz- und Leitungsband für  $T > 0$ . Die Elektronen sind hellblau, die Löcher weiß dargestellt. **a)** Halbleiter mit gleicher Zustandsdichte in Valenz- und Leitungsband, d.h.  $\mathcal{N}_L = \mathcal{N}_V$ , **b)** Halbleiter mit  $\mathcal{N}_V > \mathcal{N}_L$ , also mit der größeren Zahl von Zuständen an der Valenzbandkante.

# Intrinsic semiconductors

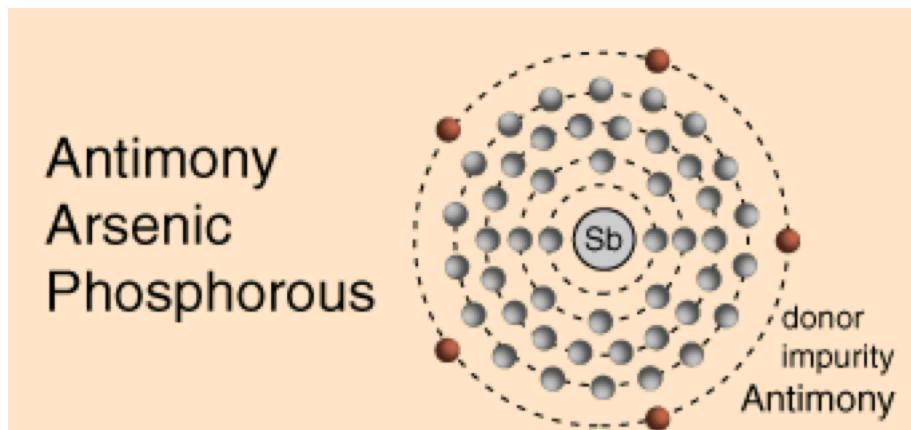
Crystalline lattice, of tetravalent elements (Si, Ge)  
4 valence electrons → covalent bonds



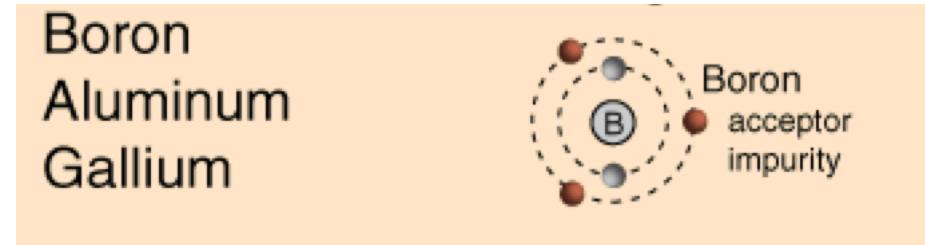
# Doping of semiconductors

n-type  
pentavalent impurities

p-type  
trivalent impurities



Boron  
Aluminum  
Gallium



# n-type

**N-Type**

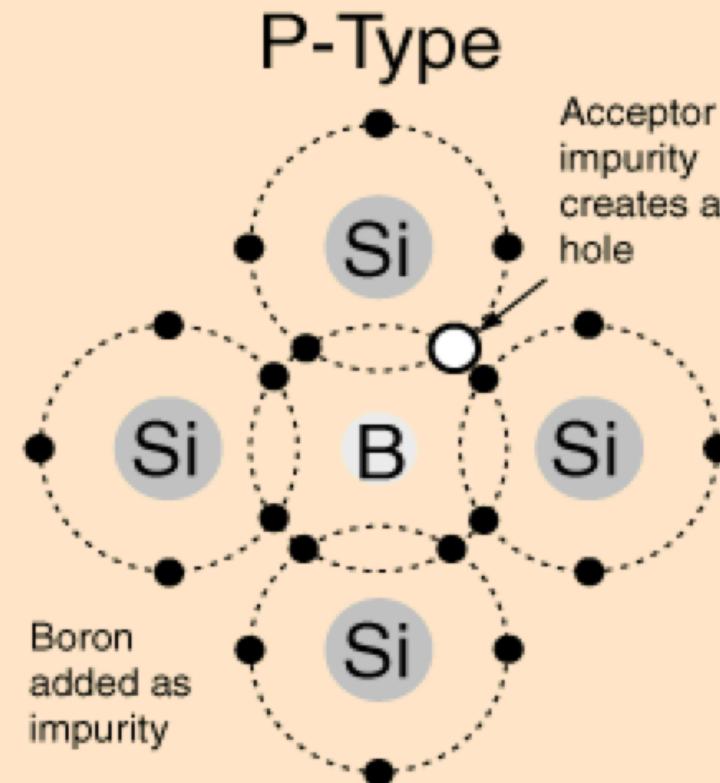
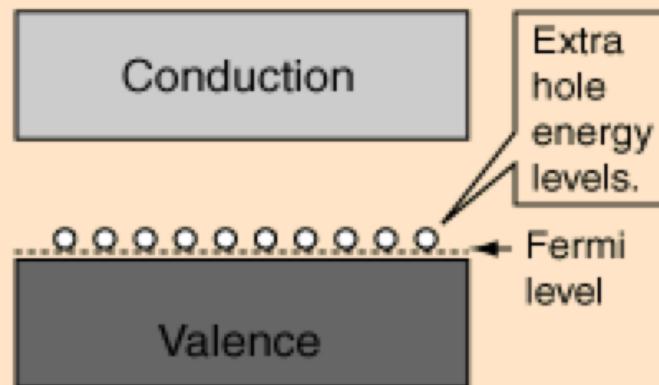
The diagram illustrates the structure of an n-type semiconductor. It shows a central antimony (Sb) atom surrounded by four silicon (Si) atoms. The Sb atom has five valence electrons instead of the four found in Si atoms. These extra electrons are shown as black dots around the Sb atom. An arrow points from one of these extra electrons to the text "Donor impurity contributes free electrons". Another label "Antimony added as impurity" is placed near the Sb atom.

The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the intrinsic semiconductor. Phosphorous may be added by diffusion of phosphine gas (PH<sub>3</sub>).

An energy level diagram for an n-type semiconductor. The diagram shows two horizontal bands: a lower grey band labeled "Valence" and an upper light grey band labeled "Conduction". Between these bands is a white rectangular region containing several black dots representing electron energy levels. A horizontal arrow labeled "Fermi level" points to a specific level within this region. A callout box labeled "Extra electron energy levels" points to the same region.

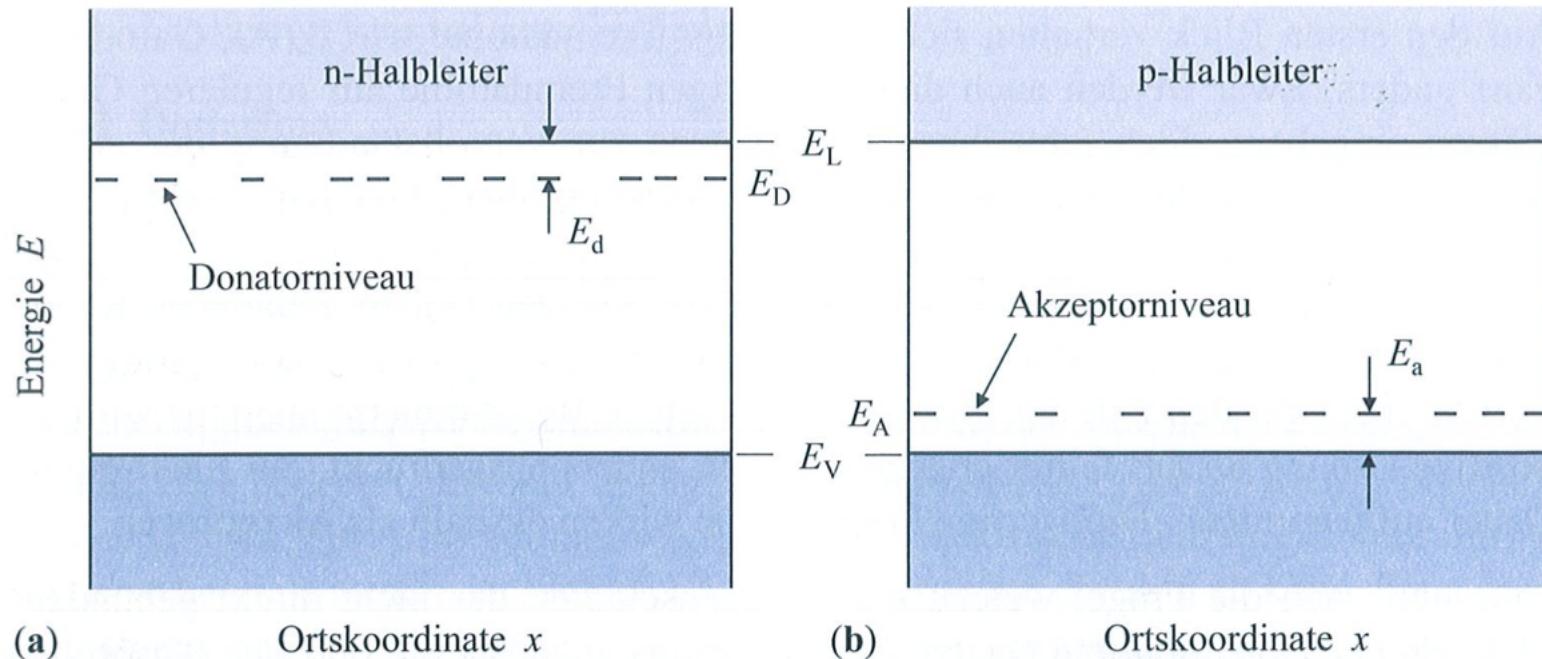
# p-type

The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons, called "holes". It is typical to use  $B_2H_6$  diborane gas to diffuse boron into the silicon material.



# Additional levels from doping elements

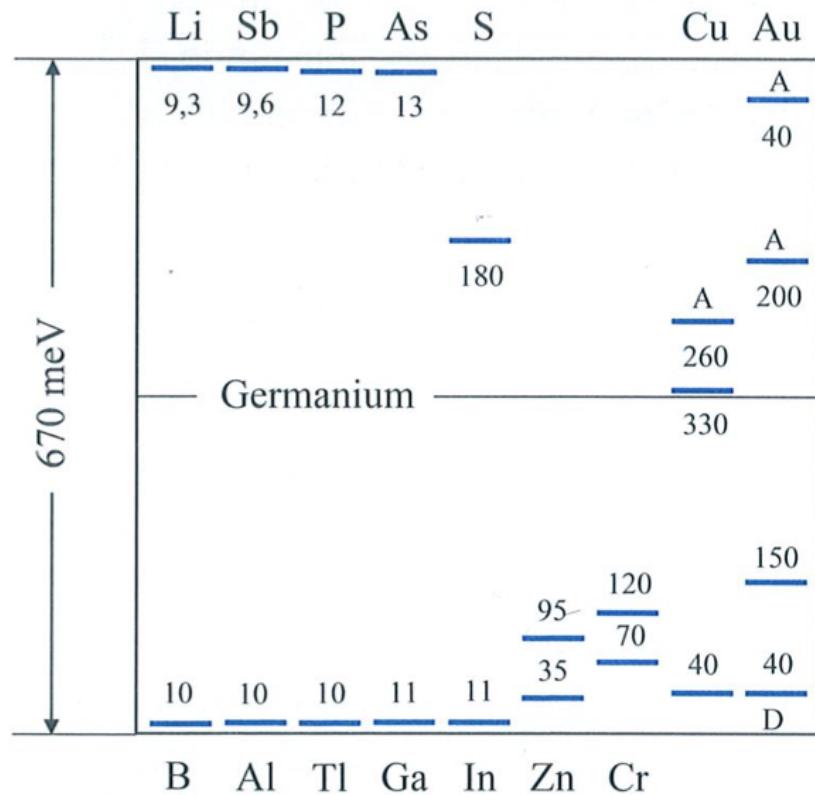
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**Bild 10.8:** Störstellenniveaus in Halbleitern. **a)** Der Grundzustand  $E_D$  der Donatoren liegt unmittelbar unter der Leitungsbandkante  $E_L$ , ihre Ionisierungsenergie ist  $E_d$ . **b)** Der Grundzustand  $E_A$  der Akzeptoren befindet sich knapp über der Valenzbandkante  $E_V$ ,  $E_a$  ist die Ionisierungsenergie der Löcher.

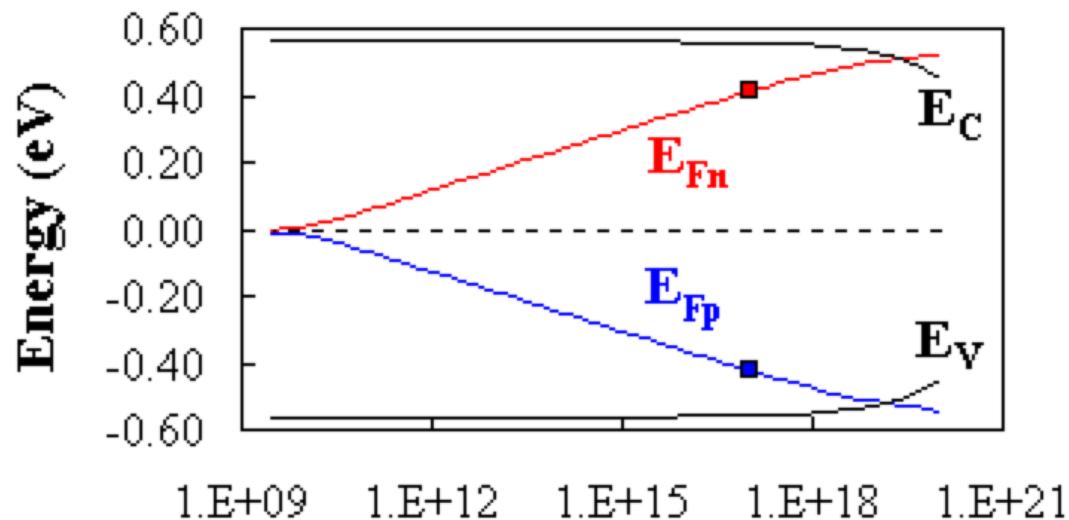
# Additional levels from doping elements

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**Bild 10.10:** Störstellenniveaus in Germanium. Die Zahlen geben den Abstand von der nächstgelegenen Bandkante an. Die Buchstaben A und D stehen für *Akzeptor* bzw. *Donator*, wenn sich die Zuordnung der Zustände nicht unmittelbar aus ihrer Lage ergibt. (Nach S.M. Sze, *Physics of Semiconductor Devices*, Wiley, New York 1981).

# Fermi level in doped semiconductors



**Doping density ( $\text{cm}^{-3}$ )**

fermiden.xls - fermiden.gif

**Fig.2.7.1** Fermi energy of n-type and p-type silicon as a function of doping density at 300 K. Shown are the conduction and valence band edges,  $E_C$  and  $E_V$ , the intrinsic energy  $E_i$ , the Fermi energy for n-type material,  $E_{Fn}$ , and for p-type material,  $E_{Fp}$ .