AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE

Modern physics

9. Electrical conductivity of solids

Outline

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9.2. Band structure
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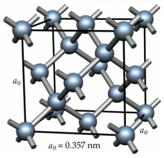
    9.5.3. The transistor

9.1. The electrical properties of solids

Computers, calculators, cellular phones are all solid-state electronic devices.



Solids are classified electrically according to the following quantities:

1. electrical resistivity ρ (ohm·m) at room temperature
2. temperature coefficient of resistivity α (K^{-1})

$$\alpha = \frac{1}{\rho}\frac{d\rho}{dT}$$

3. number density of charge carriers n (m^{-3}) defined as the number of charge carriers per unit volume

9.1. The electrical properties of solids

From measurements of room-temperature resistivity alone, we can conclude that there are materials that for practical purposes do not conduct electricity at all - **insulators**

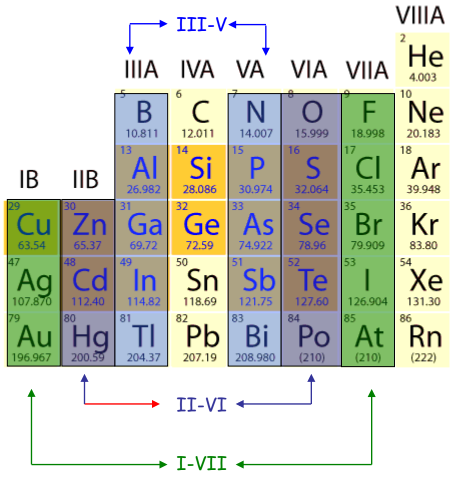
Insulator have very high electrical resistivity. Diamond, an excellent example, has a resistivity greater than that of copper by the enormous factor of about 10^{24}.

We use measurements of ρ, α and n to divide most noninsulators, at least at low temperatures, into two categories:

metals and **semiconductors**

- ρ(semiconductors)>> ρ(metals)
- α (semiconductors) high and negative (resistivity of a semiconductor *decreases* with temperature while that of a metal *increases*)
- n(semiconductors)<< n(metals)

Semiconductors in period table



IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

Group III-V

Group II-VI

Group I-VII

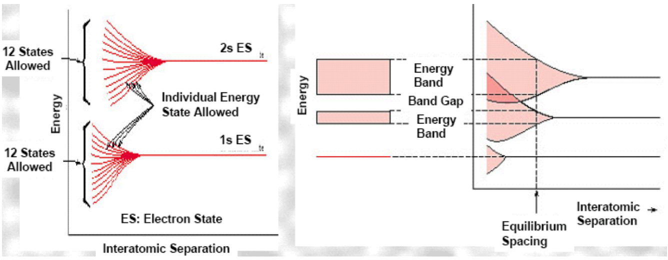
9.1. The electrical properties of solids

Cu – prototype metal, Si – prototype semiconductor

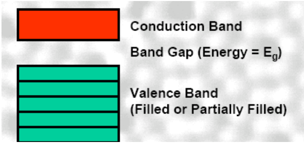
Property	Unit	Cu	Si
Type of conductor		metal	semiconductor
Resistivity, ρ	ohm·m	$2\cdot10^{-8}$	$3\cdot10^{3}$
Temperature coefficient of resistivity, α	K^{-1}	$+4\cdot10^{-3}$	$-70\cdot10^{-3}$
Number density of charge carriers	m^{-3}	$9\cdot10^{28}$	$1\cdot10^{16}$

9.2. Band structure

Isolated atom has well defined electronic **levels**. When the solid is formed, the distance between atoms decreases, the levels **split** (for N atoms each level splits into N levels).

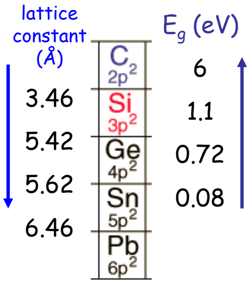


Individual energy levels of solid form energy **bands,** adjacent bands being separated by an **energy gap** (energies that no electron can possess)



9.2. Band structure

A typical band gap ranges over only a few eV. Since the number of atoms N is of the order of 10^{24}, the individual levels within a band are very close.


lattice constant (Å)

3.46

5.42

5.62

6.46

C $2p^2$

Si $3p^2$

Ge $4p^2$

Sn $5p^2$

Pb $6p^2$

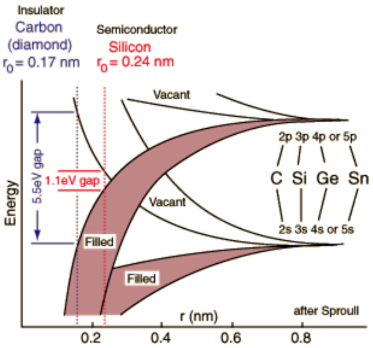
E_g (eV)

6

1.1

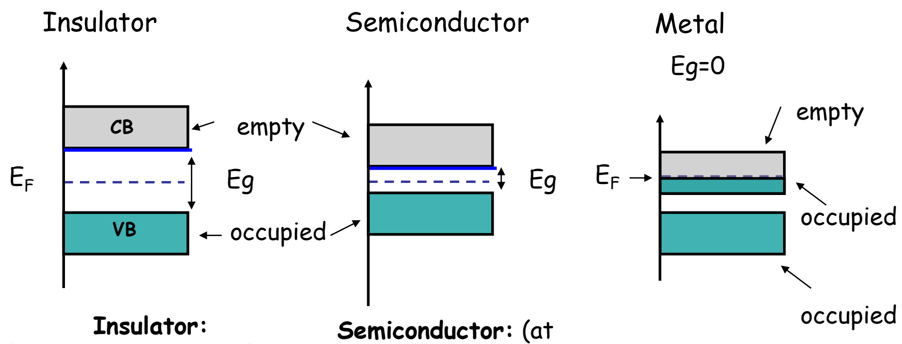
0.72

0.08



after Sproull

9.2. Band structure



Insulator:
(at room temperature)
$E_g > 4$ eV
(SiO_2: E_g = 9.1 eV,
Si_3N_4: E_g~5eV)

Semiconductor: (at room temperature):
Si: E_g =1.12 eV
Ge: E_g=0.66 eV
GaAs:E_g=1.42 eV

Metal: the highest occupied level falls near the middle of an energy band

9.3. Intrinsic and extrinsic semiconductors

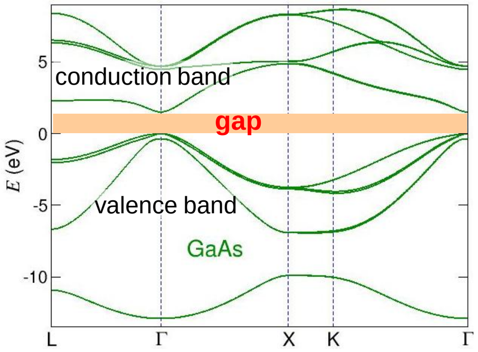
Undoped (intrinsic) semiconductors:

Band structure has energy gap E_g at the Fermi energy

conduction only if electrons are excited (e.g., thermally, optically) over the gap

Same density of electrons in conduction band and holes in valence band:

$$n_e = n_h \sim e^{-E_g/2k_BT}$$



Non-degenerate electron/hole gas in bands (i.e., no Fermi sea), transport similar to classical charged gas

9.3. Intrinsic and extrinsic semiconductors

Effective density of states

intrinsic semiconductors

$$\boxed{n_i = N_C \exp\left(-\frac{E_c - E_F}{kT}\right)}$$

$$n_e = n_h \sim e^{-E_g/2k_BT}$$

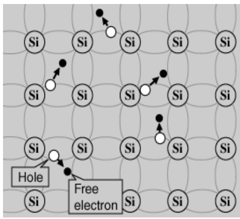
$E_g\uparrow \Rightarrow n_e\downarrow$

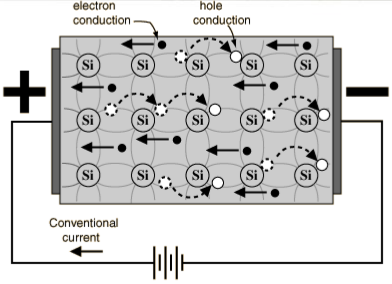
at RT

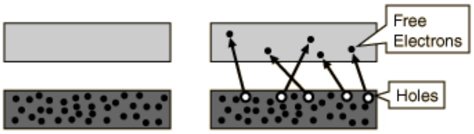
Si: Eg =1.12 eV $n_e=1.45\cdot10^{10}\,\text{cm}^{-3}$

Ge: E_g=0.66 eV $n_e=2\cdot10^{13}\,\text{cm}^{-3}$

Conduction mechanism for intrinsic semiconductors



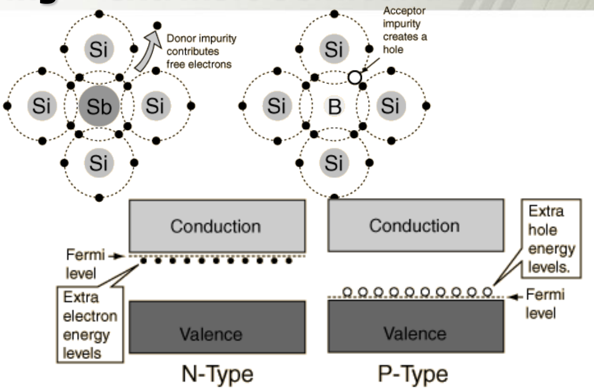




If n_e is too small in order to use the semiconductor in devices it has to be doped

Doping – extrinsic semiconductors

B	C $2p^2$	N
Al	Si $3p^2$	P
Ga	Ge $4p^2$	As
In	Sn $5p^2$	Sb
Tl	Pb $6p^2$	Bi



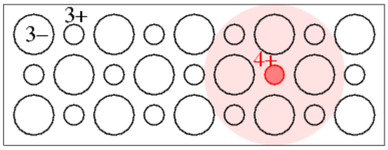
- if the valence number of dopant is smaller than that of the host the dopant is called an acceptor
- if the valence number of dopant is larger than that of the host the dopant is called a donor

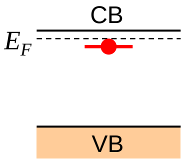
Examples of doping

Example 1: replace Ga by Si in GaAs

Si has one valence electron *more* → introduces extra electron: donor

Si^{4+} weakly binds the electron: hydrogenic (shallow) donor state

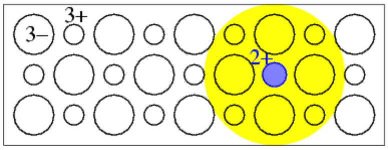


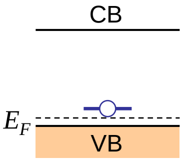


Example 2: replace Ga by Zn in GaAs

Zn has one valence electron *less* → introduces extra hole: acceptor

Zn^{2+} weakly binds the hole: hydrogenic (shallow) acceptor state



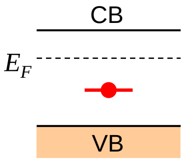


excitation energy is strongly reduced

conduction at lower temperatures

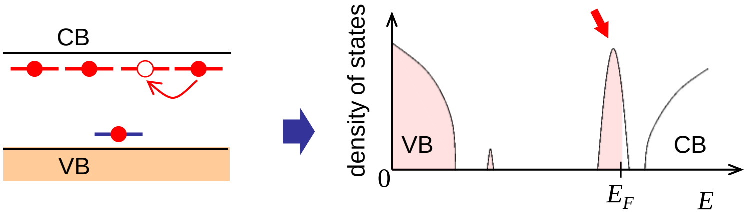
Impurity bands

- if impurity in crystal field has levels in the gap: deep levels (not hydrogenic), e.g., Te in GaAs
- both shallow and deep levels can result from native defects: vacancies, interstitials…
- if donors *and* acceptors are present: lower carrier concentration, compensation



Increasing doping:

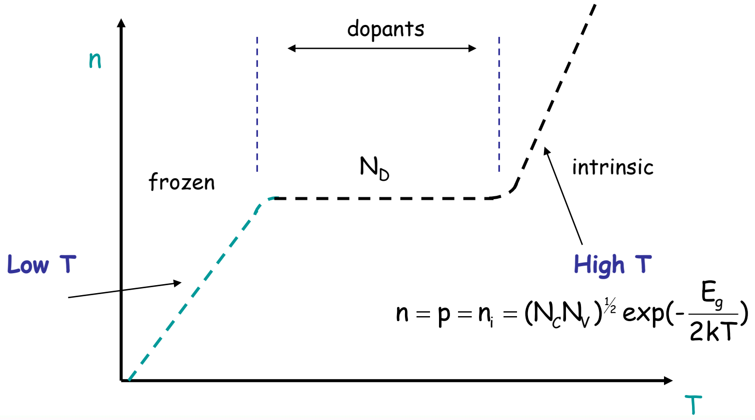
hydrogenic impurity states overlap → form impurity band



For *heavy* doping the impurity band overlaps with the VB or CB

Electrical conductivity σ

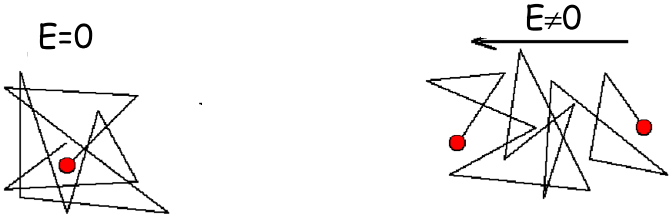
$$\sigma = ne\mu$$



$$n = p = n_i = (N_C N_V)^{1/2} \exp\left(-\frac{E_g}{2kT}\right)$$

Mobility

Mobility μ - drift velocity v_d divided by the external electric field E: $\mu = v_d/E$ (cm²/Vs)



Chaotic motion of charge carriers

Collisions at ions

drift of the charge carriers in direction of the electric field

Mobility and scattering

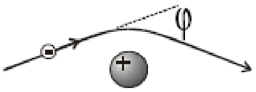
- scattering at phonons – lattice oscillations
- scattering at ionized impurities
- scattering at neutral impurities
- scattering at dislocations and other crystallographic defect

$$\tau_f \sim T^{-\zeta}, \zeta \in \frac{3}{2} \div 1$$

τ_f- average time between collisions (scattering at phonons) decreases with temperature T

Scattering at ionized impurities

Results from the electrostatic interaction between the change carriers and ionized impurities



φ decreases with velocity v_{th}, thus the average time increases with temperature

$$\tau_d \sim T^{\frac{3}{2}}$$

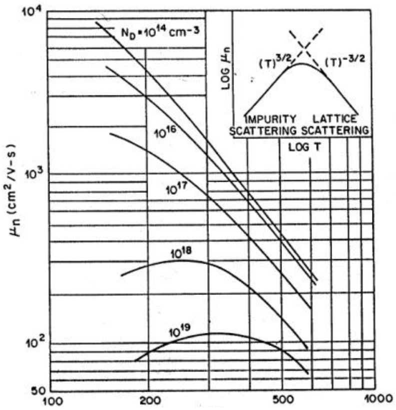
Matthiessen rule:

$$\mu = \frac{e\tau}{m^*} \qquad \frac{1}{\mu} = \sum_M \frac{1}{\mu_M}$$

$$\frac{1}{\mu} = \frac{1}{\mu_{latt}} + \frac{1}{\mu_{dop}}$$

$$\mu_{latt} \sim T^{\frac{-3}{2}}$$

$$\mu_{dop} \sim T^{\frac{3}{2}}$$

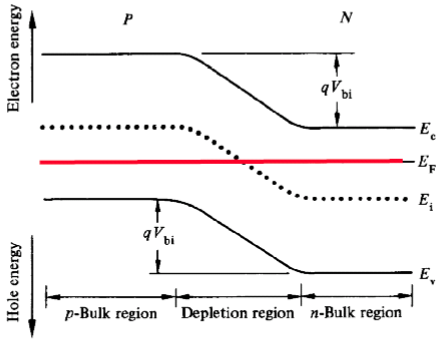


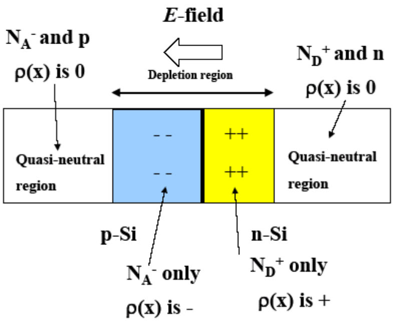
temperature

9.4. The p-n junction

A p-n junction is a single semiconducting crystal that has been selectively doped so that one region is n-type and the adjacent region is p-type. Such junctions are at the heart of all semiconductor devices.

Thermal Equilibrium





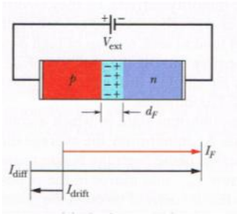
9.4. The p-n junction

The diffusion of majority carriers (electrons in n-type region, holes in p-type region) produces a diffusion current, I_{diff} that depends on the value and sign of external potential V_{ext}.

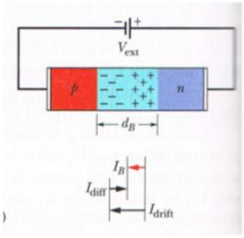
Minority carriers (holes in n-type region, electrons in p-type region) constitute a drift current, I_{drift} that is independent of the external potential V_{ext}

External voltage affects the barrier height and the width of the depletion region

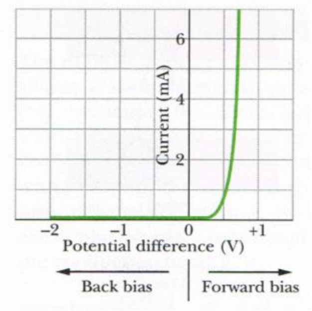
forward-bias



back-bias



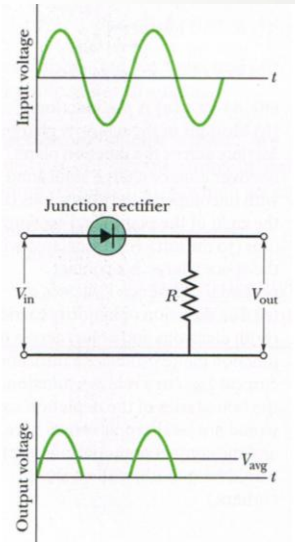
9.4. The p-n junction



A current-voltage characteristics of the p-n junction; the junction is highly conducting when forward-biased and essentially nonconducting when back-biased

9.5 Applications of semiconductors

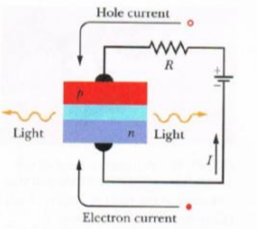
9.5.1. The junction rectifier



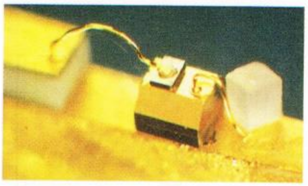
A sine wave input potential to the device is transformed into a half-wave output potential by the junction rectifier.

A rectifier acts as a closed switch (zero resistance) for one polarity of the input potential and as an open switch (infinite resistance) for the other.

9.5.2. The light-emitting diode LED



LED requires large number of electrons in the conduction band and holes in the valence band, i.e. heavily doped p-n junction and direct band gap (e.g. GaAs)



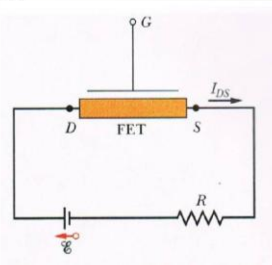
A junction laser developed at AT&T Bell Lab; size compared with a grain of salt

LED is a forward-biased p-n junction; electrons are injected into n-type and holes into p-type Light is emitted from the narrow depletion zone during recombination of electron and hole

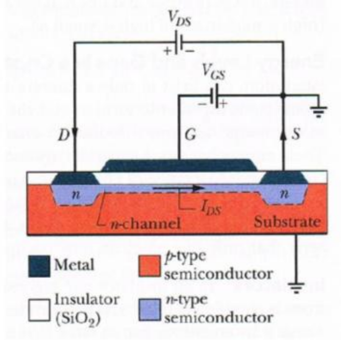
$$\lambda = \frac{c}{f} = \frac{hc}{E_g}$$

Laser requires the **population inversion** and a Fabry-Perot cavity (mirror-like opposite faces of the p-n junction)

9.5.3. The transistor



A circuit containing a generalized **f**ield-**e**ffect **t**ransistor **FET**; the electrons flow from the source terminal S to the drain D. The magnitude of current I_{DS} is controlled by the electric field set up within the FET by the potential applied to G, the gate terminal



A particular type of FET known as MOSFET. The magnitude of the I_{DS} current through the n-channel is controlled by the potential difference V_{GS} applied between the source S and the gate.