Electrical conductivity in solids

- Energy band structure
  - Silicon atoms Si (the most common semiconductor material)

Electrons potential energy of the single silicon atom

Vacuum level

The existence of the well is given electrostatic force (Coulomb law)

Distance from atom center

Discrete levels

Potential energy

Atom nucleus

Splitting of discrete levels in the crystal

- Crystalline lattice - an arrangement that is repeated periodically
  - It has the shortest distance between atoms - lattice constant
  - Pauli exclusion principle: no two electrons in its crystal can exist in the same quantum state
  - Therefore, the original discrete levels will split
  - The real number of layers depends on the number of atoms in a crystal
  - For Si $10^{28}$ m$^{-3}$

Energy levels are for more atoms very close. We reflect these levels as so called energy band

- Four electrons from each Si atom at highest levels forms valence electrons
- Valence electrons are furthers from the nucleus
- They forms mutual atoms relation and properties of materials
- Band gap - the gap between the last occupied and unoccupied band

Chemical Atomic bonds

- Metallic bond - electrons bonding are delocalized over a lattice of atoms - electron gas
- Ionic bond - bonding electron is not shared at all, but transferred. In this type of bond, the outer atomic orbital of one atom has a vacancy which allows addition of one or more electrons
- Covalent bond - one or more electrons (often a pair of electrons) are drawn into the space between the two atomic nuclei (one from each atom) with opposite spin

At low temperature

At higher temperature

Covalent bond

- At least a partial covalent bond is needed for semiconductors
- Each Si atom has four valence electrons
Why silicon is so popular?

- Easily accessible - the second most common element in the Earth's crust
- Face-centered cubic structure
- Each silicon atom has four neighbors with covalent bond

28,085

Si

14

2.33 g/cm³

Silicon

Why is silicon so popular?

Cheapest preparation of highly pure silicon
Existence of thermal oxide - Planar Technology
Relatively high resistivity of intrinsic silicon - 23 kΩ

Křemík - uvnitř monokrystalu

Monocrystalline and amorphous Si

Monocrystalline

Amorphous

Crystallographic defects

Vacancy

Interstitial defect

Frenkel pair

Fermi level \( W_F \)

- The Fermi Dirac distribution function \( f_D \)
gives the probability that a single-particle state of energy \( E \) would be occupied by an electron (at thermodynamic equilibrium)

\[
f_D(W_F) = 0.5
\]

Excited electron

\[ f_D(0) = 0 \]

\[ f_D(W_F) > 0 \]

\[ T < 0 \mathrm{K} \]

\[ T > 0 \mathrm{K} \]

Fermi level for two materials

- If we put together two materials with different Fermi level position, the level will compensate and so called thermodynamic equilibrium is set
- Electrons of connected material is demanding to get minimum Energy
- Electrons move to minimum energy
- This will be important to explain the PN junction!
Electric conductivity in solid states

- Band gap width is crucial for the value of electrical conductivity.

<table>
<thead>
<tr>
<th>Insulator</th>
<th>Semiconductor</th>
<th>Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho = 10^4 - 10^6 \ \Omega \cdot \text{cm}$</td>
<td>$\rho = 10^4 - 10^8 \ \Omega \cdot \text{cm}$</td>
<td>$\rho = 10^4 - 10^5 \ \Omega \cdot \text{cm}$</td>
</tr>
</tbody>
</table>

$\rho$ - resistivity: $\rho = 1 / \sigma$

Insulators:
- The magnitude of the band gap determines the differences between insulators, semiconductors, and metals.
- The thermal excitation mechanism is not a useful way to promote an electron to CB. Even when the melting temperature is reached in an insulator.
- Even very high electric fields are unable to excite electrons across the band gap in an insulator.

Wide band gap between VB and CB

Metals:
- No gap between valence band and conduction band.
- Those two bands are partly filled.
- Partly filled bands conduct well.
- This is the reason why metals have high conductivity.

Semiconductor energy bands
- At higher temperatures enough energy is supplied to the electron sitting at the top of the valence band, $e^-$, can make a transition to the bottom of the conduction band.
- When electron makes such a transition it leaves behind a missing electron state.
- This missing electron state is called a hole.
- Hole behaves as a positive charge carrier.

Thermal energy
- Thermal energy $= k \cdot T = 1.38 \times 10^{-23} \ \text{J/K} \times 300 \ \text{K} = 36 \ \text{meV}$
- Excitation rate is proportional to $\exp(-E_g / kT)$

Electrical field
- For low fields, this mechanism doesn’t promote electrons to the CB in common $\text{Si}$ and $\text{GaAs}$.
- An electric field of $10^8 \ \text{V/m}$ can provide an energy of the order of 1 eV. This field is enormous.

Electromagnetic radiation
- For Silicon, $E_p = 1.1 \ \text{eV}$
- $\lambda(\mu\text{m}) = \frac{1.24}{E_p} = 1.1 \ \mu\text{m}$

Band gap (Forbiden energy gap) ($E_g$)
Conclusions

- Holes contribute to current in valence band (VB) as electrons in conduction band (CB).

- **Hole is not a free particle.** It can only exist within the crystal. A hole is simply a vacant electron state.

- A transition results an equal number of electrons in CB and holes in VB.
- This is an important property of intrinsic, or undoped semiconductors.
- For extrinsic, or doped, semiconductors this is no longer true.

Electron and hole conductivity

- Holes moves in the valence band, electrons in the conduction band

Diffusion current in semiconductors

- Particles (electrons, holes) are moving from areas of high concentrations to a region of low concentrations. Diffusion current is formed

Doped (extrinsic) Semiconductor

- Intrinsic concentration of free carriers (electrons, holes) is constant in the semiconductor at a given temperature
- Generation and recombination process of electron-hole pairs is continuous process in semiconductors

- The design of electronic components need various layers with different concentrations of electrons and holes
- We do this by impurity doping semiconductors

The drift velocity and mobility

- At zero temperature, the free electron speed is relating to thermal lattice vibrations (no electric field)

- If electric field is applied across a material, the drift velocity of electrons can be described by the formula: \( v_d = \mu E \)
Doping by introducing impurities to a semiconductor is known as lattice modification. Semiconductor conductivity may easily be modified by introducing impurities (dopants) into their crystal lattice. The process of adding controlled impurities to a semiconductor is known as doping.

**P-type semiconductor**
- Doping by acceptors (element of the third group B)
- Majority carriers – holes
- Minority carriers - electrons

**N-type semiconductor**
- Doping by donors (element of the fifth group P, As)
- Majority carriers – electrons
- Minority carriers - holes

**P-N Junction**

The PN Junction

- **Depletion region** - includes the positively and negatively charged regions. The space charge region does not have any free carriers. The width of the space charge region is proportional to dopant concentration.
- **Metallurgical Junction**: The interface where the p- and n-type materials meet.
- **Na & Nd**: Represent the amount of negative and positive doping in number of charge carriers per centimeter cubed. Usually in the range of $10^{15}$ to $10^{20}$.
The result is the injection of holes into the N type.

Holes in N become minority carriers and recombine with majority electrons.

Analogous transport processes take place in conduction band with electrons in the opposite direction.

Forward bias is formed by a positive voltage on the anode.
External voltage acts against the barrier voltage. It results in decreasing of potential barrier. 

Potential

Hole Diffusion

Neutral n-region

Hole Drift

Depletion region

Electron Drift

Electron Diffusion

Neutral p-region

$E_b$ $E_n$

$E_h$ $E_n$

$E_v$

$E_n$

$E_p$

$qV_b$

$x_n$ $x_p$

$E_v = -\frac{dV_n}{dx}$

$p$ type $n$ type

$N_A x_p = N_D x_n$

The higher doped side of the junction has the narrower depletion width

when $N_A = N_D \rightarrow x_n = x_p$

The pn junction is considered biased when an external voltage is applied.

There are two types of biasing: Forward bias and Reverse bias.
Reverse bias: $V < 0$

- Reverse bias is formed by a negative voltage on the anode.
- External voltage acts along with the barrier voltage. It results in increasing of potential barrier, $V_{bi}$.
- Holes in the valence band of P can not drift to the PN junction.
- Minor holes in N, however, can overcome the PN junction and are extracted by P region.
- The concentration of the holes in N is very small, and the resulting current will be small.
- At room temperature the current is practically zero.
- Analogical process can be described for minor electrons in the opposite direction.

Properties of Diodes

- $V_D =$ Bias Voltage
- $I_D =$ Current through Diode. $I_D$ is Negative for Reverse Bias and Positive for Forward Bias.
- $I_S =$ Reverse Saturation Current.
- $V_{BR} =$ Breakdown Voltage.
- $V_{o} =$ Barrier Potential Voltage.

Ideal diode equation

$$J_{F} = q\left[ \frac{D_n}{I_n} + \frac{D_p}{I_p} \right] \exp\left( \frac{qV}{kT} \right) - 1 = J \left[ \exp\left( \frac{qV}{kT} \right) - 1 \right]$$

Multiplying by area:

$$J = I \left[ \exp\left( \frac{qV}{kT} \right) - 1 \right]$$

This equation is valid for both forward and reverse biases; just change the sign of V.