Semiconductor Devices

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lectures 30 hours
lab. exercises 30 hours

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Fundamentals of Semiconductor Physics

Chapter 1

Metal  Semiconductor  Isolator

Metal:
- Resistivity ($\rho$) decreases with increasing temperature ($T$).
- Very low resistivity.

Semiconductor:
- Resistivity ($\rho$) decreases with increasing temperature ($T$).
- Medium resistivity.

Isolator:
- Resistivity ($\rho$) increases with increasing temperature ($T$).
- Very large resistivity.
What are semiconductors?

1. They are crystals

2. They can be:
   - atom crystals like: Si, Ge, C-diamond
   - compound crystals like: GaAs, InSb, SiC, GaN

3. When they are pure, their resistivity is in a middle range
Basic semiconductors:

- **Si** - silicon
- **Ge** - germanium
- **GaAs** - gallium arsenide
- **SiC** - silicon carbide
- **GaN** - gallium nitride
Structure of crystal – energy band model

Pauli restriction – elektrons must be recognisable

single atom

atoms in crystal
Structure of silicon crystal – so called diamond structure

Crystal bond between 2 atoms

The bond arises when 2 atoms are so close that two of their valance electrons become common, which results in quantum nature attraction.

atom A  electrons  atom B
Structure of silicon crystal – so called diamond structure

Crystal bond between 2 atoms

The bond arises when 2 atoms are so close that two of their valance electrons become common, which results in quantum nature attraction

two electron bond

two atoms molecule
Structure of silicon crystal – so called diamond structure
Structure of silicon crystal – 2D representation
2D Structure of silicon crystal

$T = 0 \text{ K}$

If the temperature of crystal $T = 0\text{K}$ all the valance electrons take part in the atom bonds.
2D Structure of silicon crystal

T = 0 K

If the crystal temperature T = 0K all the valance electrons take part in the atom bonds

The crystal temperature can, however, increase and then T > 0K.

If the sufficient energy is delivered to the valance electron, it can leave its position in the interatom bond and can become a free electron.
The valance electron taking sufficient energy leaves its position in the bond and becomes free electron.

Such a free electron can move in the crystal without any restriction and is called conduct electron in contrast to the electrons in bonds called valance electrons.
The valance electron taking sufficient energy leaves its position in the bond and becomes free electron.

The empty place in the bond structure is called hole and can also move through the crystal as the result of valance electrons hopping from one bond to another.
2D Structure of silicon crystal

T > 0 K

Conduct electrons are not connected with any bonds and can freely move inside the crystal. Since they are negative charge $-q$ their movement can create an electric current.

Holes are not connected with any particular bond and can freely move inside the crystal. Since the hole means the lack of an electron, it is connected with the local excess of positive charge $+q$. This charge moves together with the hole creating an electric current.
The presented process is called *electron-hole pair generation* and has its energy band model:

$$W_g = W_c - W_v$$
2D Structure of silicon crystal

Electrons – fermions fulfilling the Pauli restriction

The presented process is called electron-hole pair generation and has its energy band model:

$$W_g = W_C - W_V$$
Dopands in Silicon  \( T = 0K \)

- **Si**  
- **Ga**
- **As**

**Acceptors**
- ***III* Mendeleiwe group*  
  - Ga, B, Al

**Donors**
- ***V* Mendeleiwe group*  
  - As, Sb, P
Dopands in Silicon  \( T > 0K \)

Ionization energy of dopands is very low

\( W_i << W_g \)
Dopands in Silicon $T > 0K$

Ionization energy of dopands is very low

$W_i << W_g$
Carrier concentration in doped semiconductor

Charge balance:
\[ n_d + N_a + n_T = p_T + N_d + p_a \]
\[ n_0 + N_a = p_0 + N_d \]

Types of semiconductors

- If \( N_a > N_d \) \( \Rightarrow \) \( p_{p0} > n_{p0} \)  p-type
- If \( N_a < N_d \) \( \Rightarrow \) \( p_{n0} < n_{n0} \)  n-type
- If \( N_a = N_d \) \( \Rightarrow \) \( p_0 = n_0 = n_i \)  i-type
Equilibrium carrier concentration

Thermodynamic equilibrium state

The state of the system being in constant temperature without any energy exchange with surroundings - so called adiabatic conditions.

The equilibrium densities of electrons and holes, $n_0$ and $p_0$, result from the balance of generation and annihilation processes:

$$g_d T = r_d T$$

$$g_T = r_T$$

Type n

$n_0, p_0$
**Statistical physics**

- It is used to describe physical phenomena that are created by huge number of elements – e.g. properties of gases that can be considered as the set of molecules.

- The phenomenon is described by the parameters that represent the behaviour of the set of elements being related to the average value of particular element feature

<table>
<thead>
<tr>
<th>Temperature</th>
<th>average kinetic energy of molecules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>average momentum of molecules</td>
</tr>
</tbody>
</table>
Statistical physics

- The set of elements is characterised by the probability function that determines the probability that the considered parametr of an element has particular magnitude.

- In the classical approach, the probability function has a bell-like shape with the maximum value corresponded to the average value of parameter (energy in the figure).
Statistical physics

- If we want to know how many particles (e.g. electrons) have their energy in the range $<W_1, W_2>$, it is enough to calculate the integral:

$$n = \int_{W_1}^{W_2} N(W) f(W) \, dW$$

where:

- $N(W)$ – state density function (in classical approach, total number of particles $N(W) = N$)
- $f(W)$ – probability that the state of energy $W$ is occupied
Statistical physics

Classical approach – Boltzmann distribution

\[ f(W) = \exp\left(-\frac{W}{kT}\right) \]

Quantum approach – Fermi-Dirac distribution

\[ f(W) = \frac{1}{\exp\left(\frac{W - W_F}{kT}\right) + 1} \]

\( W_F \) – Fermi energy \((Fermi\ level)\)
Statistical physics

Classical approximation –

\( f(W) = \exp\left( - \frac{W - W_F}{kT} \right) \)

Quantum approach – Fermi-Dirac distribution

\( f(W) = \frac{1}{\exp\left( \frac{W - W_F}{kT} \right) + 1} \)

\( W_F \) – Fermi energy \((\text{Fermi level})\)
Statistical physics

Classical approximation – \( (W - W_F) > 2kT \)

\[
f(W) = \exp\left( - \frac{W - W_F}{kT} \right)
\]

If this approach can be used to estimate the electron and hole density in semiconductor, such a semiconductor is called non-degenerated.

Only such semiconductors will be considered in our lectures.
Equilibrium carrier concentration

Classical approximation for electrons

Concentration of electrons in conduction band:

$$n_0 = \int_{W_c}^{W_{c1}} N(W) f(W) dW$$

Under the assumption: $W_{c1} \Rightarrow \infty$

$$n_0 = N_C \exp\left( -\frac{W_C - W_F}{kT} \right)$$

$N_C$ – effective density of states in the conduction band

$W_{c1}$

$W_c$

Conduction band

states occupied by electrons
Equilibrium carrier concentration

Classical approximation for holes

Concentration of holes in valance band:

\[
p_0 = \int_{W_{v1}}^{W_v} N(W)(1 - f(W))dW
\]

Under the assumption: \( W_{v1} \Rightarrow -\infty \)

\[
p_0 = N_v \exp\left(-\frac{W_F - W_v}{kT}\right)
\]

\( N_v \) – effective density of states in the valance band
Equilibrium in intrinsic semiconductor

From the equilibrium condition:

$$N_C \exp\left(-\frac{W_C - W_{Fi}}{kT}\right) = N_V \exp\left(-\frac{W_{Fi} - W_V}{kT}\right)$$

one can calculate $W_{Fi}$, the Fermi energy for intrinsic semiconductor:

$$W_{Fi} = \frac{1}{2}(W_C + W_V) + \frac{1}{2}kT \ln \frac{N_V}{N_C} = \frac{1}{2}(W_C + W_V) + \frac{3}{4}kT \ln \frac{m_{eh}}{m_{ee}}$$
Equilibrium in doped semiconductor

Transformation of electron equation:

\[ n_0 = N_C \exp \left( -\frac{W_C - W_F}{kT} \right) = \]

\[ = N_C \exp \left( -\frac{W_C - W_{Fi} + W_{Fi} - W_F}{kT} \right) = \]

\[ = N_C \exp \left( -\frac{W_C - W_{Fi}}{kT} \right) \exp \left( -\frac{W_{Fi} - W_F}{kT} \right) = \]

\[ = n_i \exp \left( -\frac{W_{Fi} - W_F}{kT} \right) \]
Equilibrium in doped semiconductor

Transformation of hole equation:

\[ p_0 = N_V \exp\left(-\frac{W_F - W_V}{kT}\right) = \]

\[ = N_V \exp\left(-\frac{W_F - W_{Fi} + W_{Fi} - W_V}{kT}\right) = \]

\[ = n_i \exp\left(\frac{W_{Fi} - W_F}{kT}\right) \]
Equilibrium in doped semiconductor

Product of hole and electron concentration:

\[ n_0 p_0 = n_i \exp \left( -\frac{W_{Fi} - W_F}{kT} \right) n_i \exp \left( \frac{W_{Fi} - W_F}{kT} \right) \]

\[ n_0 p_0 = n_i^2 \]

At constant temperature \( n_0 p_0 \) is constant independently on the dopant concentration
Equilibrium in doped semiconductor

Transformation of hole and electron product:

\[ n_i^2 = n_0 p_0 \]

\[
\begin{align*}
n_0 p_0 &= N_C \exp\left(-\frac{W_C - W_F}{kT}\right) N_V \exp\left(-\frac{W_F - W_V}{kT}\right) = \\
&= N_C N_V \exp\left(-\frac{W_C - W_V}{kT}\right) = N_C N_V \exp\left(-\frac{W_g}{kT}\right) = \\
&= B^2 \left(\frac{T}{300}\right)^3 \exp\left(-\frac{W_g}{kT}\right)
\end{align*}
\]

\[ n_i = f(T) \]
Carrier concentration in doped semiconductor

Typ n

\[ n_0 = n_d + n_T \]
\[ p_0 = p_T \]

\( T_s \) – saturation temperature
\( T_i \) – intrinsic temperature

Fundamentals of Semiconductor Physics

Chapter 1
Carrier concentration in doped semiconductor

\[ \ln n_0, \ln p_0 \]

\[ n_0, n_i, p_0 \]

\[ T_s, T_i, T_s \text{ - saturation temperature, } T_i \text{ - intrinsic temperature} \]

Type n
Thermal limitation for semiconductor devices

If semiconductor devices are to keep their data sheet ratings, the concentration of majority carriers cannot change considerably. **Condition 1:** It is true when $T_{\text{min}}$ not lower than $T_s$.

For Si $T_{\text{min}} \approx -50 ^\circ \text{C}$
Thermal limitation for semiconductor devices

If semiconductor devices are to keep their data sheet ratings, the concentration of majority carriers cannot change considerably. **Condition 2:** It is true when $T_{\text{max}}$ lower than $T_i$.

For Si $T_{\text{max}} < 400 \, ^\circ\text{C}$
Thermal limitation for semiconductor devices

If semiconductor devices are to keep their data sheet ratings, the concentration of majority carriers cannot change considerably. *Condition 2*: It is true when $T_{\text{max}}$ lower than $T_i$.

Typical ranges defined for silicon devices in catalogues:

<table>
<thead>
<tr>
<th>Range</th>
<th>[°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial</td>
<td>0 – 70</td>
</tr>
<tr>
<td>Industrial</td>
<td>-25 – 85</td>
</tr>
<tr>
<td>Extended industrial</td>
<td>-40 – 125</td>
</tr>
<tr>
<td>Military</td>
<td>-55 – 125</td>
</tr>
</tbody>
</table>
Current filamentation – hot spot

If $T$ inside $\langle T_s, T_i \rangle$, the negative thermal feedback occurs:

Current is pushed out from warmer area and heat dissipation decreases.
Current filamentation – hot spot

If $T$ inside $<T_s, T_i>$, the negative thermal feedback occurs:

Current is pushed out from warmer area and heat dissipation decreases.
Current filamentation – hot spot

If $T_{\text{outside}} < T_s, T_i >$, the positive thermal feedback occurs:

- Current is squeezed in warmer area.
- Heat dissipation increases.

Silicon chip

Safe area

Current is squeezed in warmer area and heat dissipation increases
Current filamentation – hot spot

If $T_{\text{outside}} < T_s, T_i$, the positive thermal feedback occurs:

Current is squeezed into small area and hot spot is generated.
Nonequilibrium carrier concentration

Equilibrium concentrations

\[ n_0, p_0 \]

Nonequilibrium concentrations

\[ n = n_0 + \Delta n \]
\[ p = p_0 + \Delta p \]

\( \Delta n, \Delta p \) – excess concentrations

usually:
\[ \Delta n = \Delta p \]
Nonequilibrium carrier concentration

Quasi-Fermi level

\[ n = n_0 + \Delta n \]
\[ p = p_0 + \Delta p \]

\[ n = N_c \exp \left( - \frac{W_c - W_F}{kT} \right) + \Delta n = N_c \exp \left( - \frac{W_c - W_{Fe}}{kT} \right) \]
\[ p = N_v \exp \left( - \frac{W_F - W_v}{kT} \right) + \Delta p = N_v \exp \left( - \frac{W_{Fh} - W_v}{kT} \right) \]

\[ n_0 = N_c \exp \left( - \frac{W_c - W_F}{kT} \right) \]
\[ p_0 = N_v \exp \left( - \frac{W_F - W_v}{kT} \right) \]
Nonequilibrium carrier concentration

**Quasi-Fermi level**

\[
n = n_0 + \Delta n = N_c \exp \left( - \frac{W_c - W_{Fe}}{kT} \right)
\]

\[
p = p_0 + \Delta p = N_v \exp \left( - \frac{W_{Fh} - W_v}{kT} \right)
\]

\(W_{Fe}\) – quasi-Fermi level for electrons

\(W_{Fh}\) – quasi-Fermi level for holes
Recombination processes

Equilibrium state:

- $g_T$ – rate of electron-hole pairs thermal generation
- $r_T$ – rate of electron-hole pairs thermal annihilation

Steady state
constant carrier concentrations
Recombination processes

Non-equilibrium state:

- $g_T$ – rate of electron-hole pairs thermal generation
- $g_r$ – rate of electron-hole pairs radiative generation
- $r$ – rate of electron-hole pairs annihilation

Steady state

constant carrier concentrations

$g_r + g_T = r$