$p$-$n$ junctions

combine $p$- and $n$-type semiconductor region

most important characteristics: **rectification**

(current flows “easily“ only in one direction)

important as rectifier but also: Basic building block in bipolar transistors, field-effect transistors, LED‘s, solar cells ....

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![Graph showing current-voltage characteristics of a typical silicon $p$-$n$ junction.](attachment:image.png)

**Fig. 1** Current–voltage characteristics of a typical silicon $p$–$n$ junction.

Formation of a p-n junction:

Conceptionally:
Take a p-type SC and combine it with an n-type SC

The actual process is of course different ...

S. M. Sze, “Physics of Semiconductor Devices”
Static conditions – thermodynamic equilibrium

We start with:

Establish contact: $e^-$ and $h^+$ concentration gradient!

→ electrons diffuse from the n-side into the p-side and holes diffuse from the p-side into the n-side → DIFFUSION CURRENT!
Acceptor and donor ions are fixed!

→ **negative space charge** on the p-side of the junction

→ **positive space charge** on the n-side of the junction

→ **depletion region**

(virtually no free carriers → charged dopands!)

**electric field**

→ **DRIFT CURRENT**!

(In the opposite direction of the diffusion current)

D. A. B. Miller, lecture notes, Stanford University. 1999
electrons \hspace{1cm} \text{holes}

**Diffusion current density**

\[
j_{n,\text{diff}} = e D_n \frac{d n}{d x} \hspace{2cm} j_{p,\text{diff}} = -e D_p \frac{d p}{d x}
\]

\(D_n, D_p\) \ldots \text{diffusion coefficients given by the Einstein relations}

\[
D_n = \frac{kT}{e} \mu_n \hspace{2cm} D_p = \frac{kT}{e} \mu_p
\]

\(\mu_n\) and \(\mu_p\) \ldots \text{mobilities of electrons and holes, respectively}

**Drift current density**

\[
j_{n,\text{drift}} = e \mu_n nF \hspace{2cm} j_{p,\text{drift}} = e \mu_p pF
\]

\(F\) \ldots \text{driving electric field}
What happens, if we apply an electric field to the semiconductor?

\[ F = -\frac{dU}{dx} = \frac{1}{e} \frac{dE}{dx} \]

\( F \) … electrostatic potential

\( E \) … \( E_C, E_V, E_{vac}, E_i \) (intrinsic Fermi level)
Junction in thermodynamic equilibrium

Let’s look at the hole current density ...

\[ j_p = e \mu_p p F - e D_p \frac{dp}{dx} \]

\[ p = n_i \exp \left( \frac{E_i - E_F}{k_B T} \right) \]

\[ \rightarrow \frac{dp}{dx} = n_i \exp \left( \frac{E_i - E_F}{k_B T} \right) \frac{1}{k_B T} \left( \frac{d E_i}{dx} - \frac{dE_F}{dx} \right) \]

\[ \rightarrow \frac{dp}{dx} = \frac{p}{k_B T} \left( \frac{d E_i}{dx} - \frac{dE_F}{dx} \right) \]

and

\[ F = \frac{1}{e} \int dE_i \]

D. A. B. Miller, lecture notes, Stanford University, 1999
\[
\begin{align*}
\dot{j}_p &= e\mu_p p \left( \frac{1}{e} \frac{dE_i}{dx} - e \frac{k_B T}{e} \mu_p \frac{p}{k_B T} \left( \frac{d E_i}{d x} - \frac{dE_F}{dx} \right) \right) \\
\dot{j}_p &= \mu_p p \frac{dE_F}{dx}
\end{align*}
\]

**Thermodynamic equilibrium:** The current flow across the junction has to be zero!

\[
\frac{dE_F}{dx} = 0
\]

In the thermodynamic equilibrium (i.e., if no charge carriers are injected), the Fermi energy in the device is CONSTANT!
What is the electrostatic potential difference between the p-side and the n-side?

\[ eV_{bi} = \text{minus} V_{bi} \quad \text{... built in potential} \]
But: How do the bands inside the depletion region really look like?
Assume abrupt junction:

Red: assumed abrupt junction (abrupt changes of the net charges between the depletion region and the p and n regions)
Potential from Poisson equation

\[
\frac{d^2 V}{dx^2} = -\frac{\rho}{\varepsilon}
\]

\(\rho\) ... charge density; \(\varepsilon\) ... dielectric constant

for \(-x_p \leq x < 0\)

\[
\frac{d^2 V}{dx^2} = \frac{eN_A}{\varepsilon}
\]

for \(0 < x \leq x_n\)

\[
\frac{d^2 V}{dx^2} = -\frac{eN_D}{\varepsilon}
\]

And as a side-condition:

\[
N_A x_p = N_D x_n
\]
Solving these differential equations allows us to calculate:

- The **field-distribution** in the depletion region
- The **maximum field** in the depletion region
- The **width of the depletion region**
- The “**shape**“ of the **band bending**
- The **capacitance** of the diode
- .....
Biasing a diode:

**Forward bias of** $V_F$:
- total electrostatic potential across junction decreases by $V_F$
- depletion layer width decreases

**Reverse bias of** $V_R$:
- total electrostatic potential across junction increases by $V_F$
- depletion layer width increases

The system is no longer in thermodynamic equilibrium!
→ current will flow!
Fig. 8  Schematic representations of depletion layer width and energy band diagrams of a p-n junction under various biasing conditions. (a) Thermal-equilibrium condition. (b) Forward-bias condition. (c) Reverse-bias condition.

S. M. Sze, "Semiconductor Devices – Physics and Technology"
**Current through diode**

**Applying a voltage:** disturb balance between diffusion current and drift current

**Forward bias:** drift current reduced in comparison to diffusion current

→ enhanced diffusion of holes from p-side to n-side

→ enhanced diffusion of electrons from n-side to p-side

**minority-carrier injection → current**

**Reverse bias:** increase of electrostatic potential across depletion region

→ reduce minority carrier concentrations

→ reduce also diffusion current
Fig. 14  Depletion region, energy band diagram, and carrier distribution. (a) Forward bias. (b) Reverse bias.
Ideal current-voltage characteristics

Several approximations ... including no generation or recombination of carriers in the depletion region

Using the “semiconductor statistics“ and current equations we discussed before (after a somewhat lengthy derivation):

\[ j = j_S \left( e^{eV/k_BT} - 1 \right) \]

\( j_S \) ... saturation current (contains diffusion coefficients, diffusion lengths and equilibrium concentrations of the minority carriers in the p and n regions)

• Current grows exponentially with the applied voltage in forward direction

• Current density saturates at \(-j_S\) in reverse direction
Fig. 16  Ideal current–voltage characteristics. (a) Cartesian plot. (b) Semilog plot.
Deviations from the ideal characteristics

Most relevant for our purposes:

**Recombination current**

e\text{-} from n-type region and h\text{+} from p-type region recombine in the depletion region

\rightarrow added current in forward direction

can happen through traps (heating of the device)
or through the emission of a photon (LED)

**Photocurrent**

Optical absorption \rightarrow extra pair of e\text{-} and h\text{+} in depletion region

\rightarrow extra reverse current
Heterostructure diodes

Band bending of course also happens in heterostructures with different doping levels

But then in addition to the **band bending also band offsets**

\[ \phi_{wp}, \phi_{wn}, E_{Fe}, V_{bi}, \Delta E_c, \Delta E_v \]

D. A. B. Miller, lecture notes, Stanford University, 1999
Fig. 4.20. Illustration of various AlGaAs - GaAs double heterostructures. (a) The basic double heterostructure diode. (b) A structure where the GaAs is lightly $p$ doped, at zero bias, and (c) in forward bias. (d) A structure where the GaAs is lightly $n$ doped, at zero bias, and (e) in forward bias. (f) The refractive index in the heterostructure, showing the higher index in the GaAs (after Wood).
Metal-semiconductor contacts (Schottky-contacts)

(here we again assume that there are no interface dipoles and we neglect effects like mirror charges and Fermi level pinning ...)


Some similarities to a p-njunction (metal plays the “role“ of the p or n type semiconductor)

But also certain differences ...
n-type semiconductor:

\[E_F \text{ constant !}\]

\(e^-\) or \(h^+\) flow from semiconductor into metal

built-in voltage \(V_{bi}\) and band bending in the SC

\(\rightarrow\) depletion region

potential barrier \(\Phi_{bn}\) (lowered by Schottky effect)
Charging, fields and shape of band bending

S. M. Sze, “Semiconductor Devices – Physics and Technology”

Fig. 2 (a) Energy band diagram of an isolated metal adjacent to an isolated n-type semiconductor under nonequilibrium condition. (b) Energy band diagram of a metal-semiconductor contact in thermal equilibrium. (c) Charge distribution. (d) Electric-field distribution.
Charge transport through Schottky-junctions

different from p-n junction:

• charge transported by the majority carriers

• **thermionic emission** of majority carriers from the semiconductor over the potential barrier into the metal

• equilibrium: balanced by flow of electrons from metal into semiconductor

\[ j = j_s \left( e^{eV / k_B T} - 1 \right) \]

**Fig. 6** Current transport by the thermionic emission process. (a) Thermal equilibrium. (b) Forward bias. (c) Reverse bias.

**rectification** with current density given by: \[ j = j_s \left( e^{eV / k_B T} - 1 \right) \]
Ohmic contact:

Definition: metal-semiconductor contact with “negligible“ contact resistance

How can this be realized?

very high doping of the semiconductor

→ depletion region extremely short

→ e\(^-\) and h\(^+\) can “easily” tunnel through resulting very thin barrier
**Ohmic contacts**

**no rectification !**

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*D. A. B. Miller, lecture notes, Stanford University, 1999*