Diode in electronic circuits

Symbolic representation of a Diode in circuits

Anode  Cathode
(+)  (-)

$i_D$

- An ideal diode conducts the current only in one direction
- “Arrow” shows direction of the current in circuit
- *Positive* polarity of the voltage at an *anode* and negative one at a cathode correspond to a *forward* bias condition
- *Minus* at the *anode* and plus at the cathode correspond to *reverse* biasing
Diode as a non-linear resistor

Current-Voltage (I-V) Characteristics

I-V of a LINEAR RESISTOR

\[ R = \frac{v}{i} \]

I-V of an IDEALIZED DIODE

\[ R \to 0 \]

\[ R \to \infty \]
I-V Characteristic of an Ideal Diode

\[ J = J_s (e^{qV/kT} - 1) \]

- At room temperature \( T=300K \) the thermal voltage \( kT/q = 26 \text{ meV} \)
- For a Si diode the typical value of the saturation current \( J_s \approx 10^{-10} \text{ A/cm}^2 \)

For a high forward bias \( V \gg 26 \text{ mV} \):

\[ J \approx J_s e^{qV/kT} \]

- The forward current shows an exponential dependence

For a high reverse bias \( V < 0, V \ll -26 \text{ mV} \):

\[ J \approx -J_s \]

- Reverse current of diodes is quite small
I-V Characteristic of a Diode in \textit{semilogarithmic} scale

- The slope in logarithmic scale can be used to define the \textit{non-ideality} factor $n$
- The intersection of $lgI$-V characteristic with vertical axis gives the value of \textit{saturation current} $J_S$
- The current increase differs from \textit{exponential} at high forward bias voltage
I-V Characteristic of a Real Diode

A Silicon (Si) Diode

- The *typical* voltage drop across a Si diode at forward bias is 0.7V

A Germanium (Ge) Diode

- The *typical* voltage drop across a Ge diode at forward bias is 0.4V
At high current I-V characteristic become to be linear.

Series Resistance $R_S$ describes the experimental $I$-$V$ characteristic.

Ideal Diode $R_S$
Breakdown of a Diode at Reverse Voltage

- The reverse current starts to increase rapidly at some high voltage $V_B$

![Graph showing the relationship between voltage ($v(V)$) and current ($i(A)$). The graph starts flat, then curves sharply as $v$ increases beyond $V_B$. The slope $R_{diff} = \frac{dv}{di}$ is indicated on the graph.]

- This caused by *avalanche* or *tunnel* breakdown

- The breakdown voltage $V_B$ can be as high as 100$^{th}$ Volts or can be purposely made a small down to 3-5V

- Zener diode can be used as a *voltage reference* source

- *Differential resistance* $R_D$ is an important device parameter
Point-by-point measurements of I-V characteristics using DMM

- Accurate measurements of current and voltage using two-display DMM require a floating voltage source
- Make sure that the ground clip on the power supply is disconnected!
Metal-semiconductor junction

Work function $\Phi$ characterizes minimum energy that has to be transferred to the electron in order to remove it from the material.

After Metal and Semiconductor are brought in contact the Fermi energy should be constant throughout the system in thermal equilibrium.
chottky barrier and built-in potential barrier

When $\Phi_{\text{METAL}} > \Phi_{\text{SEMICONDUCTOR}}$ electrons from semiconductor will flow into lower energy states in metal

When electrons move from metal to semiconductor they are stopped by Schottky barrier

$$\Phi_{B0} = \Phi_M - \chi$$

When electrons in CB move from semiconductor to metal they are stopped by built-in potential barrier

$$V_{\text{bi}} = \Phi_M - \Phi_S = \Phi_{B0} - (E_C - E_F)$$
When electrons are moved away from the metal-semiconductor interface they leave charge of the ionized donors uncompensated.

Depletion region charge is $N_D \cdot W$.

$$W = \sqrt{\frac{2 \cdot \varepsilon \cdot \varepsilon_0 \cdot V_{bi}}{q \cdot N_D}}$$
**Reverse bias**

*Positive voltage is applied to n-semiconductor side*

Barrier for electron motion from metal to semiconductor remains unchanged and if high enough no current increase will flow through the structure.

Reversely biased Schottky diode can be seen as a parallel plate capacitor with plate separation equal to depletion region width.

\[
C = \frac{q \cdot \varepsilon \cdot \varepsilon_0 \cdot N_D}{\sqrt{2 \cdot (V_{bi} + V)}}
\]
Forward bias

Negative voltage is applied to n-semiconductor side

Barrier for electron motion from semiconductor to metal decreases

Electrons with kinetic energies

\[ E > q \cdot (V_{bi} - V) \]

can overcome barrier and flow to metal, hence, conduct current through the structure

\[ J = A^* \cdot T^2 \cdot \exp \left( -\frac{q \cdot \Phi_{B0}}{k \cdot T} \right) \cdot \left[ \exp \left( \frac{q \cdot V}{k \cdot T} \right) - 1 \right] \]

\[ A^* = \frac{4 \cdot \pi \cdot q \cdot m_n^* \cdot k^2}{h^3} \]

- Richardson constant

Rectifier

I

V
n- and p-semiconductors at distance

Due to difference in work functions between n- and p-type semiconductors the electrons can lower their energy if they move from n- to p-semiconductor.
Gedanken experiment

Large gradients of electrons and holes at the pn-interface (metallurgical junction) will drive holes from p- to n-semiconductor and electrons from n- to p-semiconductor. Electrons coming from n- to p-semiconductor will encounter large number of holes and recombine with them (same with holes from p-semiconductor).

The uncompensated charge of Donors (n-side) and Acceptors (p-side) will build internal electric field that will stop diffusion of electrons and holes.
The built-in potential maintains equilibrium (compensates for diffusion currents) so no net current is produced by $V_{bi}$.

$$V_{bi} = \frac{k \cdot T}{q} \cdot \ln\left(\frac{N_D \cdot N_A}{n_i^2}\right)$$
Depletion region

Equations:
\[
\frac{dE}{dx} = \frac{\rho(x)}{\varepsilon \cdot \varepsilon_0}, \quad \rho(x) = \begin{cases} 
q \cdot N_D, & -x_n < x < 0 \\
q \cdot N_A, & 0 < x < x_p 
\end{cases}
\]

\[
x_n \cdot N_D = x_p \cdot N_A
\]

\[
W = x_n + x_p = ?
\]

Solution:
\[
W = \left( \frac{2 \cdot \varepsilon \cdot \varepsilon_0 \cdot V_{bi}}{q} \cdot \left[ \frac{1}{N_D} + \frac{1}{N_A} \right] \right)^{1/2}
\]
pn-junction reverse bias

Zero bias

Reverse bias (”+” to n, “-” to p)

\[ W = \left( \frac{2 \cdot \varepsilon \cdot \varepsilon_0 \cdot V_{bi}}{q} \cdot \left[ \frac{1}{N_D} + \frac{1}{N_A} \right] \right)^{\frac{1}{2}} \]

\[ W = \left( \frac{2 \cdot \varepsilon \cdot \varepsilon_0 \cdot (V_{bi} + |V|)}{q} \cdot \left[ \frac{1}{N_D} + \frac{1}{N_A} \right] \right)^{\frac{1}{2}} \]

Under reverse bias both the depletion region width and electric field at metallurgical junction increase.
Under reverse bias both the depletion region width and electric field at metallurgical junction increase.

Depletion layer capacitance decrease.
Forward bias

Forward bias ("-" to n, "+" to p)

Energy barrier (built-in potential) is lowered and diffusion currents of minority electron and holes will flow.

\[ J = J_S \cdot \left( \exp \left( \frac{q \cdot V}{k \cdot T} \right) - 1 \right) \]

\[ J_S = \left( \frac{q \cdot D_p \cdot p_{0n}}{L_p} + \frac{q \cdot D_n \cdot n_{0p}}{L_n} \right) \]

Rectifier