P-n junctions are an integral part of several electronic and optoelectronic devices. Has many applications: photodiodes, solar cells, LEDs, laser diodes, rectifiers, capacitors. Also key elements in Metal-Oxide-Silicon Field-Effects-Transistors (MOSFETs) and Bipolar Junction Transistors (BJTs). We will therefore first discuss the basic principles of a p-n junction.
• A p-n junction (p-n diode) consists of two regions of n-type and p-type semiconductors.
• Shows a pronounced rectifying behavior.
• The p-type region with an acceptor density $N_a$, the n-type region has a donor density $N_d$.
• We assume shallow dopants.
• Electron density in the n-type region is approximately equal to the donor density: $n \sim N_d$.
• Hole density in the p-type region is approximately equal to the donor density: $p \sim N_a$. 

**p-n Junction**

![Diagram of p-n Junction](image)
• Assume uniformly doped p and n regions.
• Assume abrupt junction: transition between the two regions is abrupt.
• A one-sided abrupt p-n junction: one where one region is more highly doped than the other.
• Contact to the p-type region = anode, contact to the n-type region = cathode.
• Initially both semiconductors are totally neutral.
• The concentration of positive and negative carriers are quite different on opposite sides of the junction.

• Thermal energy-powered diffusion of positive carriers into the n-type material and negative carriers into the p-type material occurs.
• The n-type material acquires an excess of positive charge near the junction and the p-type material acquires an excess of negative charge.
• Eventually diffuse charges build up and an electric field is created which drives the minority charges and eventually equilibrium is reached.
• A region develops at the junction called the depletion region. This region is essentially undoped or just intrinsic silicon.
Flatband Diagram

- Flatband diagram: when both semiconductor regions are brought together.
- Is not an equilibrium state.
- Conduction and valence band energies are aligned.
- Fermi energies not automatically aligned.
- Electrons and holes will move to achieve thermal equilibrium.

Energy Band Diagram

(a) Before  (b) After
Thermal Equilibrium

• To attain thermal equilibrium, electrons near the junction diffuse across the junction into the \( p \)-type region where hardly any electrons are present.
• This process leaves the ionized donors behind, creating a region around the junction, which is depleted of mobile carriers.
• Holes near the junction diffuse across the junction into the \( n \)-type region where hardly any holes are present.
• This process leaves the ionized acceptors behind, creating a region around the junction, which is depleted of mobile carriers.

Thermal Equilibrium

• This region is the depletion region, extending from \( x = -x_p \) to \( x = x_n \).
• The charge due to the ionized donors and acceptors causes an electric field, which in turn causes a drift of carriers in the opposite direction.
• The diffusion of carriers continues until the drift current balances the diffusion current, thereby reaching thermal equilibrium as indicated by a constant Fermi energy.
Energy Band Diagram in Thermal Equilibrium

- In thermal equilibrium, no external voltage is applied between the p-n regions.
- There is an internal potential, \( \phi_i \), caused by the workfunction difference between the n-type and p-type semiconductors.
- This is the built-in potential = potential across the depletion region in thermal equilibrium.
- Is equal to the difference between the Fermi energies, \( E_{Fn} \) and \( E_{Fp} \), divided by the electronic charge.
- Also equals the sum of the bulk potentials of each region, \( \phi_n \) and \( \phi_p \), since the bulk potential quantifies the distance between the Fermi energy and the intrinsic energy.

The Built-In Potential

\[ \phi = V_f \ln \frac{N_d N_a}{n_i^2} \]
Forward and Reverse Bias

- Forward bias is when a positive voltage, $V_a$, is applied to the anode (the p-type region) relative to the cathode (the n-type region).
- Reverse bias corresponds to a negative voltage applied to the anode.
- At forward bias, the potential across the semiconductor decreases.
- At forward bias, depletion layer width decreases.
- At reverse bias, the potential across the semiconductor increases.
- At reverse bias, the depletion layer width increases.
- The total potential across the semiconductor equals the built-in potential minus the applied voltage: $\phi = \phi_I - V_a$

A p-n Junction under Reverse and Forward Bias

[Diagram showing energy levels and potential changes under reverse and forward bias]
Diode Circuit Connections

- Reversed biased
- Forward biased

PN junction under various bias conditions

- $V_A = 0$
- $V_A > 0$
- $V_A < 0$

Hole diffusion current
Hole drift current
Electron diffusion current
Electron drift current
A p-n Junction under Forward Bias

(a) Equilibrium ($V_A = 0$)

(b) Forward bias ($V_A > 0$)

Fig. 6.1 (Perret, 1990)

A p-n Junction under Reverse Bias

(c) Reverse bias ($V_A < 0$)

Figure 6.1 Continued
**Effect of bias on diffusion current**

- When the diode forward-bias-voltage is increased, the barrier for electron and hole diffusion current decreases linearly. See the band diagram.

- Since the carrier concentration decreases exponentially with energy in both bands, diffusion current increases exponentially as the barrier is reduced.

- As the reverse-bias-voltage is increased, the diffusion current decreases rapidly to zero, since the fall-off in current is exponential.

**Effect of bias on drift current**

- When the reverse-bias-voltage is increased, the net electric field increases, but drift current *does not change*. In this case, drift current is limited *NOT* by HOW FAST carriers are swept across the depletion layer, but rather HOW OFTEN.

- The number of carriers drifting across the depletion layer is small because the number of minority carriers that diffuse towards the edge of the depletion layer is small.

→ To a first approximation, the drift current *does not change* with the applied voltage.
Effect of bias on the “net” current

- $|I_{\text{drift}}|$ does not change with applied voltage, $V_A$
- $|I_{\text{diff}}|$ varies exponentially with applied voltage
  (Why?) $|I_{\text{diff}}| = I_0 \exp \left( \frac{V_A}{V_{\text{ref}}} \right)$ where $I_0$ and $V_{\text{ref}}$ are constants.
- Net current $= I_{\text{diff}} - I_{\text{drift}}$
- At equilibrium, $V_A = 0$; Net current $= 0$

At any applied voltage, $V_A$, 

$$I = I_0 \exp \left( \frac{V_A}{V_{\text{ref}}} \right) - I_{\text{drift}} = I_0 \left( \exp \left( \frac{V_A}{V_{\text{ref}}} \right) - 1 \right)$$

since $I_{\text{drift}} = I_0$ at any voltage.

I-V characteristics of real p-n diodes

- An approximation to the current in the PN junction region is given by $I = I_0 (\exp \frac{V}{V_T} - 1)$.
- Both $I_0$ and $V_T$ are temperature dependent.
- For a real diode, other factors are also important.
- Edge effects around the border of the junction cause the actual reverse current to increase slightly with reverse voltage.
- Finite conductivity of the doped semiconductor ultimately restricts the forward current to a linear increase with increasing applied voltage.
### Ideal Diode

- I-V Characteristics

#### Real Diode

- Reverse Bias Breakdown
  - Maximum reverse bias voltage that can be applied to a p-n diode.
  - Characterized by the rapid increase of the current under reverse bias.
  - Corresponding applied voltage is referred to as the breakdown voltage.
  - The breakdown voltage is a key parameter of power devices.
  - Two mechanisms can cause breakdown, namely avalanche multiplication and quantum mechanical tunneling of carriers through the bandgap.
  - Neither of the two breakdown mechanisms is destructive.
• However, heating caused by the large breakdown current and high breakdown voltage causes the diode to be destroyed unless sufficient heat sinking is provided.

Breakdown in silicon at room temperature can be predicted using the following empirical expression for the electric field at breakdown.

\[ E_{br} = \frac{4 \times 10^5}{\left(1 - \frac{1}{2} \log(M/10^{15}) \right)} \text{ V/cm} \]

Assuming a one-sided abrupt p-n diode, the corresponding breakdown voltage can then be calculated, yielding:

\[ \Psi_{br} = -\Delta + \frac{E_{br}^2 \xi}{2qN} \]

The resulting breakdown voltage is inversely proportional to the doping density if one ignores the weak doping dependence of the electric field at breakdown. The corresponding depletion layer width equals:

\[ w_{br} = \frac{E_{br} \xi}{qN} \]
**Edge Effects**

- Planar p-n diodes have higher electric fields at the edges.
- Diodes will break down in the regions with higher fields.
- One has to take into account the radius of curvature of the metallurgical junction at the edges.
- Breakdown voltages can be improved with proper edge termination.
- Edge passivation by ion implantation, oxides etc used.

---

**The Zener Breakdown**

- There are several other types of diodes beside the junction diode.
- As the reverse voltage increases the diode suffers a breakdown which can be avalanche or zener.
- *Zener breakdown*: when the electric field near the junction becomes large enough to excite valence electrons directly into the conduction band.
Avalanche Breakdown

- *Avalanche breakdown*: caused by impact ionization of electron-hole pairs.

- When the minority carriers are accelerated in the electric field near the junction to sufficient energies that they can excite valence electrons through collisions.

- When applying a high electric field, carriers gain kinetic energy and generate additional electron-hole pairs through impact ionization.