The PN Junction

Formation, Depletion Region, and Built-in Potential

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Why Study the PN Junction?

Foundation of Semiconductor Devices:

- Diodes, BJTs, MOSFETs all contain pn junctions
- Rectification and switching
- Controls current flow

Key Questions:

- What happens when p-type meets n-type?
- How does the depletion region form?
- What is built-in potential?
- How do carriers move across the junction?

Applications:

- Rectifier diodes (AC to DC)
- Signal processing
- Voltage regulation
- Light-emitting diodes (LEDs)
- Solar cells

Lecture Objectives

- Understand pn junction formation
- Analyze depletion region
- Calculate built-in potential
- Understand drift and diffusion currents

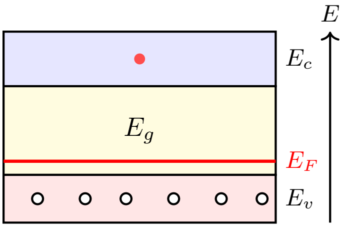
p-Type Semiconductor

Carrier Concentrations:

- Acceptor concentration: N_A
- Majority carriers (holes): $p \approx N_A$
- Minority carriers (electrons): $n \approx \dfrac{n_i^2}{N_A}$
- Charge neutral overall

Energy Levels:

- Fermi level E_F near valence band
- Many holes in valence band
- Few electrons in conduction band



p-type: $p \gg n$

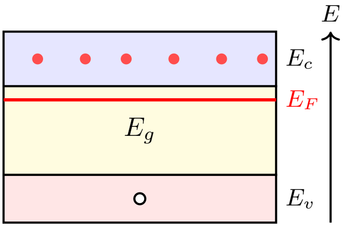
n-Type Semiconductor

Carrier Concentrations:

- Donor concentration: N_D
- Majority carriers (electrons): $n \approx N_D$
- Minority carriers (holes): $p \approx \frac{n_i^2}{N_D}$
- Charge neutral overall

Energy Levels:

- Fermi level E_F near conduction band
- Many electrons in conduction band
- Few holes in valence band



n-type: $n \gg p$

Separated p-type and n-type

p-type
$p = N_A$

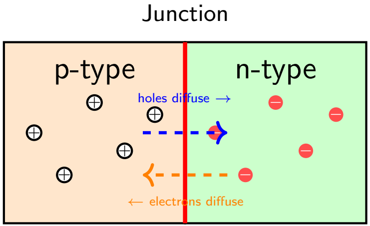
n-type
$n = N_D$

- **Different Fermi levels**: $E_{F,p} < E_{F,n}$
- **No current**: Semiconductors are separated
- **What happens when we bring them together?**

Bringing p-type and n-type Together

At $t = 0^+$ (instant of contact):

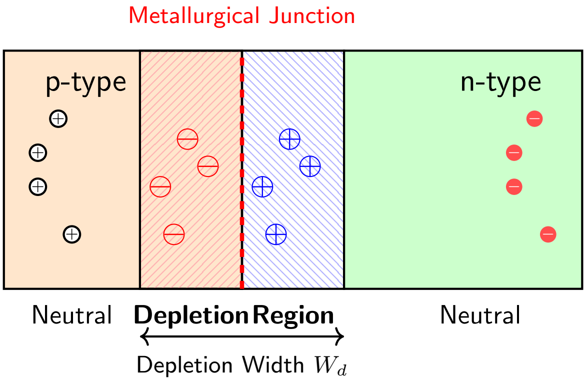
- Large concentration gradients exist
- Electrons in n-side: high concentration
- Holes in p-side: high concentration
- **Diffusion begins**



Diffusion Process:

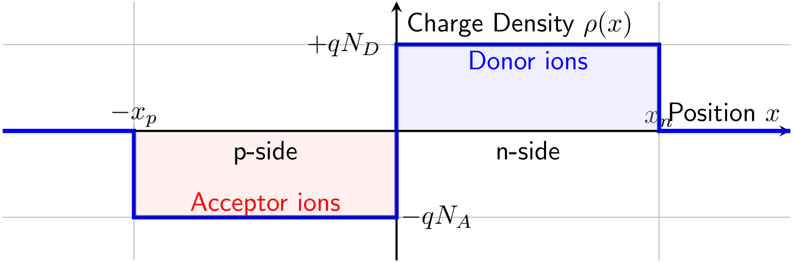
- Electrons diffuse from n → p
- Holes diffuse from p → n
- Leaves behind ionized dopants
- Creates space charge region

Formation of Depletion Region



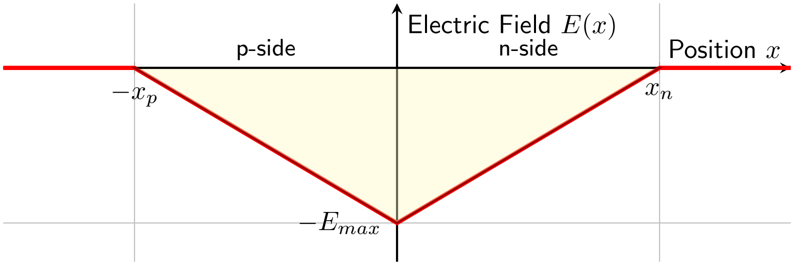
- **Depletion region**: Region depleted of mobile carriers (electrons and holes)
- **Space charge**: Fixed ionized dopant atoms create electric field
- **Self-limiting process**: Electric field opposes further diffusion

Charge Distribution at Junction



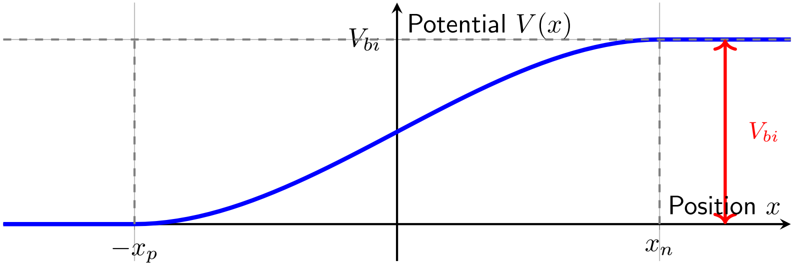
- **p-side depletion**: Negatively charged acceptor ions ($-qN_A$)
- **n-side depletion**: Positively charged donor ions ($+qN_D$)
- **Charge neutrality**: $qN_Ax_p = qN_Dx_n$ (total charge $= 0$)

Electric Field in Depletion Region



- **Direction**: Electric field points from n-side to p-side (from + to -)
- **Maximum at junction**: E_{max} occurs at metallurgical junction
- **Creates built-in potential**: $V_{bi} = -\int E(x)dx$

Built-in Potential

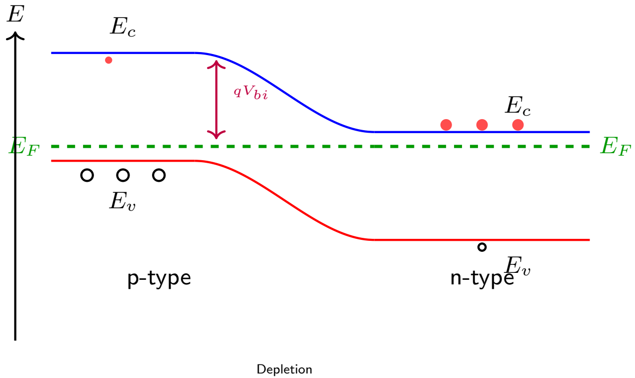


Built-in Potential Formula

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

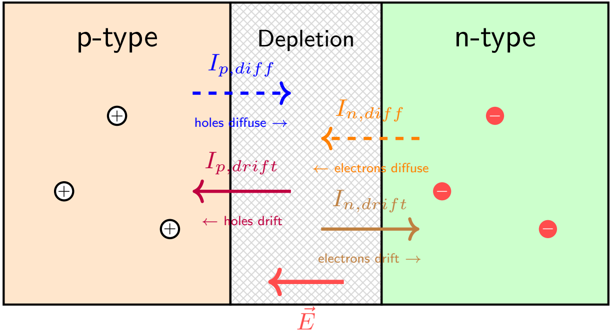
where $V_T = \frac{kT}{q} \approx 26$ mV at room temperature (300 K)

Energy Band Diagram at Thermal Equilibrium



- **Fermi level is flat**: At thermal equilibrium, E_F is constant throughout
- **Band bending**: Energy bands bend by qV_{bi} across depletion region
- **Barrier for electrons and holes**: Prevents unlimited diffusion

Drift and Diffusion Currents at Equilibrium

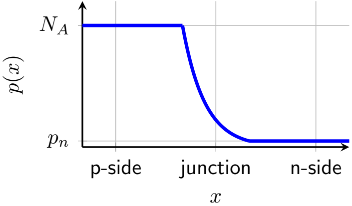


At Thermal Equilibrium

- $I_{p,diff} + I_{p,drift} = 0$ (hole current = 0)
- $I_{n,diff} + I_{n,drift} = 0$ (electron current = 0)
- Total current $I = 0$

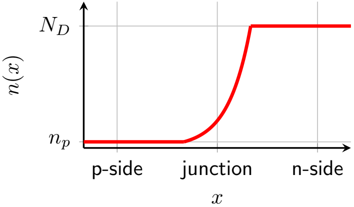
Concentration Profiles

Hole Concentration $p(x)$:



- High on p-side ($p \approx N_A$)
- Low on n-side ($p \approx \frac{n_i^2}{N_D}$)
- Exponential in depletion region

Electron Concentration $n(x)$:



- Low on p-side ($n \approx \frac{n_i^2}{N_A}$)
- High on n-side ($n \approx N_D$)
- Exponential in depletion region

Key Formulas Reference

Parameter	Formula
Built-in potential	$V_{bi} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$
Thermal voltage	$V_T = \frac{kT}{q} \approx 26$ mV
Depletion width	$W = x_p + x_n$
Charge neutrality	$N_A x_p = N_D x_n$

Parameter	Formula
Max electric field	$E_{max} = \frac{q N_D x_n}{\epsilon_s}$
Equilibrium condition	$I_{diff} + I_{drift} = 0$
Minority carriers (p-side)	$n_p = \frac{n_i^2}{N_A}$
Minority carriers (n-side)	$p_n = \frac{n_i^2}{N_D}$

Summary: PN Junction Fundamentals

1. **Junction Formation**:
   - Diffusion of carriers creates depletion region
   - Space charge creates electric field
   - Built-in potential opposes further diffusion
2. **Depletion Region**:
   - Depleted of mobile carriers
   - Contains fixed ionized dopants
   - Width depends on doping concentrations
3. **Thermal Equilibrium**:
   - Fermi level is flat throughout device
   - Energy bands bend by qV_{bi}
   - Diffusion and drift currents balance (total current $= 0$)
4. **Key Concepts**:
   - Built-in potential V_{bi} cannot be measured externally
   - Barrier prevents majority carrier flow
   - Foundation for understanding diode operation under bias