PN Junction External Under Bias

Forward Bias, Reverse Bias, and Breakdown

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Lecture Overview

Previously: PN Junction at Equilibrium

- Built-in potential V_{bi}
- Depletion region formation
- Flat Fermi level
- Zero net current

Today: PN Junction Under Bias

- Apply external voltage
- Break equilibrium
- Control current flow
- Understand diode operation

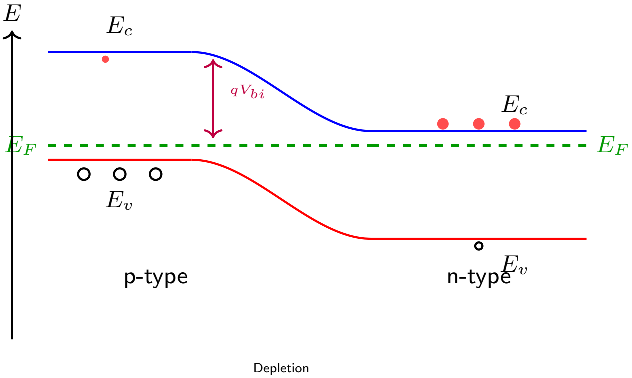
Lecture Objectives

- Review equilibrium condition
- Analyze forward bias operation
- Analyze reverse bias operation
- Understand breakdown mechanisms
- Derive diode I-V characteristics

Applications:

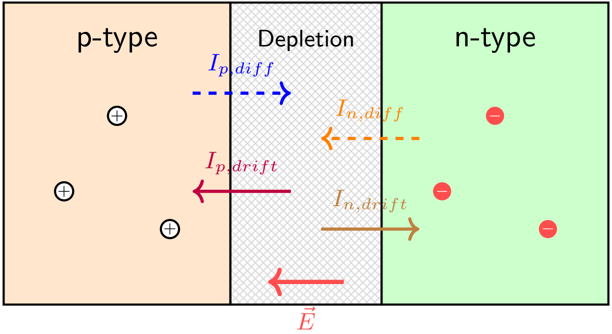
- Rectifier circuits
- Voltage regulation (Zener diodes)
- Switching circuits
- Power supplies

Review: Energy Band Diagram at Thermal Equilibrium



- **No applied voltage**: $V_A =$ open circuit
- **Flat Fermi level**: System in thermal equilibrium
- **Barrier height**: qV_{bi} prevents carrier diffusion

Review: Drift and Diffusion at Equilibrium



At Equilibrium (V_A = open circuit)

- $I_{p,diff} = -I_{p,drift}$ (currents cancel)
- $I_{n,diff} = -I_{n,drift}$ (currents cancel)
- $I = 0$ (no net current)

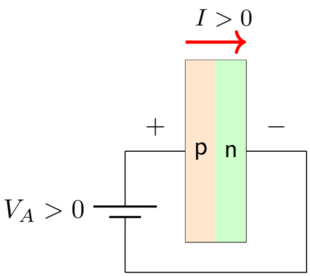
Forward Bias: Circuit Configuration

Definition:

- Connect positive terminal to p-side
- Connect negative terminal to n-side
- Applied voltage: $V_A > 0$

Effect on Junction:

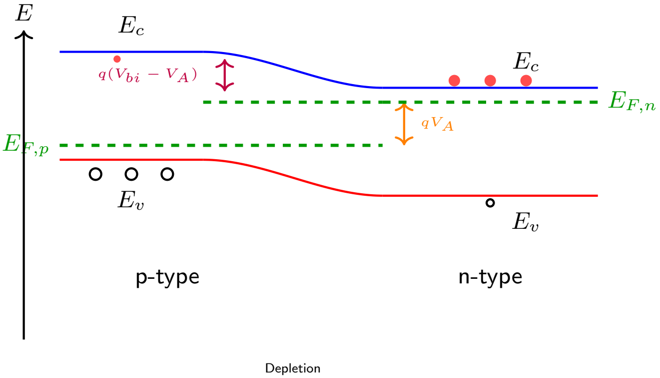
- Reduces barrier height
- Barrier becomes: $q(V_{bi} - V_A)$
- Increases carrier injection
- Large current flows



Key Point

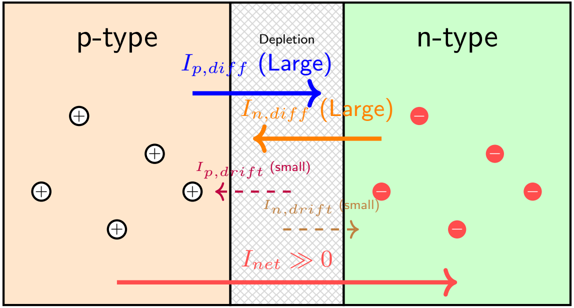
Forward bias **reduces** the potential barrier, allowing majority carriers to flow across junction.

Forward Bias: Energy Band Diagram



- **Reduced barrier**: From qV_{bi} to $q(V_{bi} - V_A)$
- **Split Fermi levels**: System NOT in equilibrium, $E_{F,n} - E_{F,p} = qV_A$
- **Narrower depletion region**: Less space charge

Forward Bias: Current Flow



Forward Bias Current

- **Diffusion dominates**: $I_{diff} \gg I_{drift}$
- **Holes injected** from p $\rightarrow$ n (minority carriers in n-side)
- **Electrons injected** from n $\rightarrow$ p (minority carriers in p-side)
- **Large current**: $I = I_S(e^{V_A/V_T} - 1) \approx I_S e^{V_A/V_T}$ for $V_A > 0$

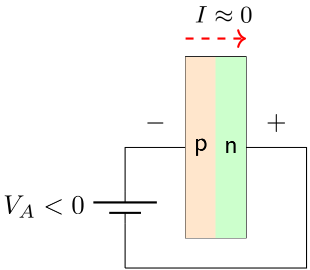
Reverse Bias: Circuit Configuration

Definition:

- Connect negative terminal to p-side
- Connect positive terminal to n-side
- Applied voltage: $V_A < 0$

Effect on Junction:

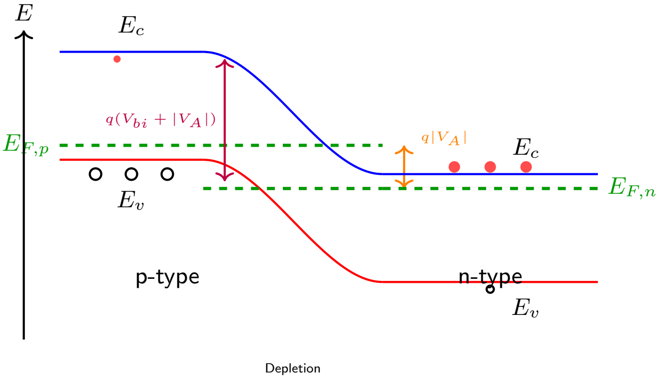
- Increases barrier height
- Barrier becomes: $q(V_{bi} - V_A) = q(V_{bi} + |V_A|)$
- Prevents carrier injection
- Very small current (leakage)



Key Point

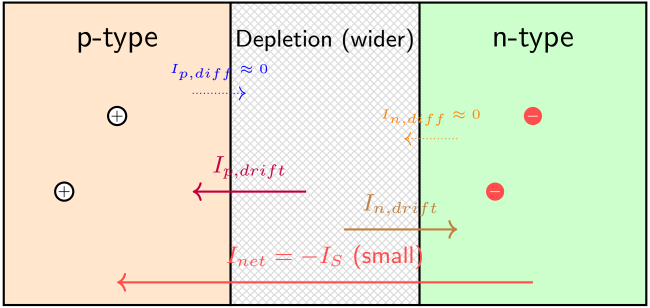
Reverse bias **increases** the potential barrier, preventing majority carrier flow. Only small leakage current flows.

Reverse Bias: Energy Band Diagram



- **Increased barrier**: From qV_{bi} to $q(V_{bi} + |V_A|)$
- **Split Fermi levels**: $E_{F,n} - E_{F,p} = q|V_A|$ (reversed from forward bias)
- **Wider depletion region**: More space charge

Reverse Bias: Current Flow



Reverse Bias Current

- **Diffusion blocked**: Potential Energy barrier too high for majority carriers to diffuse
- **Drift dominates**: Minority carriers swept across junction by E field
- **Reverse saturation current**: $I \approx -I_S$ (constant, small)
- Typically: $I_S \sim 10^{-12}$ to 10^{-15} A (pA to fA range)

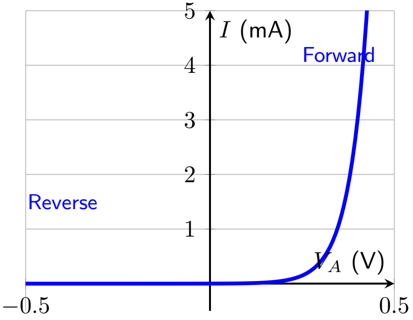
The Shockley Diode Equation

Diode Equation

$$I = I_S \left(e^{V_A/V_T} - 1\right)$$

where:

- I_S = reverse saturation current
- V_A = applied voltage
- $V_T = \frac{kT}{q} \approx 26$ mV at 300K



Forward Bias ($V_A > 0$):

$$I \approx I_S e^{V_A/V_T}$$

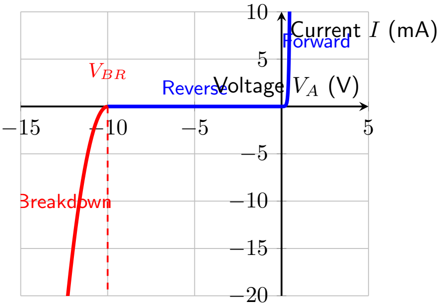
Reverse Bias Breakdown

What is Breakdown?

- Large reverse voltage applied
- Barrier becomes very large
- Depletion region very wide
- Electric field becomes extremely high
- Sudden large reverse current

Breakdown Voltage V_{BR}:

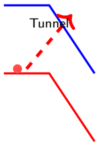
- Voltage at which breakdown occurs
- Depends on doping concentration
- Higher doping $\rightarrow$ lower V_{BR}
- Typical: 50V to 1000V
- Zener diodes: 2V to 200V



Breakdown Mechanisms

1. Zener Breakdown

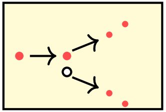
- Quantum tunneling effect
- Electrons tunnel through barrier
- Direct band-to-band tunneling



Zener (Tunneling)

2. Avalanche Breakdown

- Higher breakdown voltage ($V_{BR} > 5$V)
- Accelerated carriers create e-h pairs
- Chain reaction (avalanche)



Avalanche (Impact)

Key Differences

- Zener: Heavy doping, low V_{BR}, tunneling
- Avalanche: Light doping, high V_{BR}, impact ionization
- Both produce large reverse current at breakdown

Summary: PN Junction Under Bias

1. **Equilibrium (No Bias)**:
   - Flat Fermi level, $V_A = 0$
   - Barrier: qV_{bi}
   - No net current
2. **Forward Bias** $(V_A > 0)$:
   - Reduced barrier: $q(V_{bi} - V_A)$
   - Large diffusion current
   - $I \approx I_S e^{V_A/V_T}$
   - Narrower depletion region
3. **Reverse Bias** $(V_A < 0)$:
   - Increased barrier: $q(V_{bi} + |V_A|)$
   - Small drift current
   - $I \approx -I_S$ (constant)
   - Wider depletion region
4. **Breakdown** $(V_A < -V_{BR})$:
   - Zener: Tunneling (heavy doping, low V_{BR})
   - Avalanche: Impact ionization (light doping, high V_{BR})
   - Used in Zener diodes for voltage regulation

Key Formulas and Parameters

Parameter	Formula
Diode current	$I = I_S(e^{V_A/V_T} - 1)$
Thermal voltage	$V_T = \frac{kT}{q} \approx 26$ mV
Forward bias	$I \approx I_S e^{V_A/V_T}$
Reverse bias	$I \approx -I_S$

Parameter	Value/Condition
Turn-on voltage	$V_{on} \approx 0.7$ V (Si)
Sat. current	$I_S \sim 10^{-12}$ A
Breakdown	$V_A < -V_{BR}$
Zener range	2V – 200V

Important Concepts

- Forward bias: Exponential I-V relationship
- Reverse bias: Nearly constant current $-I_S$
- Breakdown: Controlled in Zener diodes, destructive in regular diodes
- Depletion width: Varies with applied voltage