

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

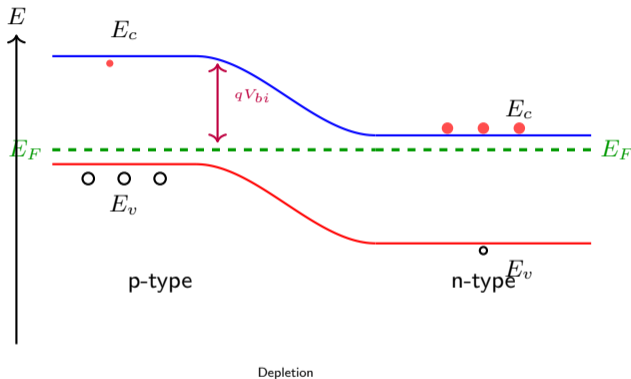
Lecture Objectives

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

Applications:

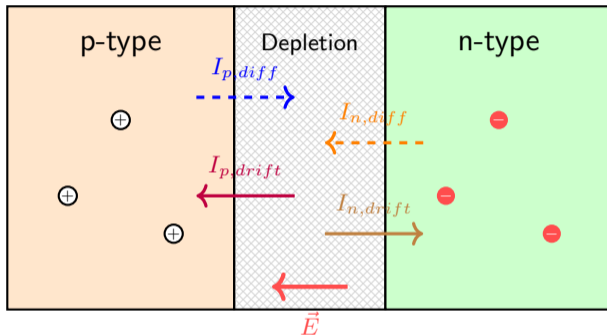
- Rectifier circuits
- Voltage regulation (Zener diodes)
- Switching circuits
- Power supplies

Review: Energy Band Diagram at Thermal Equilibrium



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

Review: Drift and Diffusion at Equilibrium



At Equilibrium ($V_A = \text{open circuit}$)

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

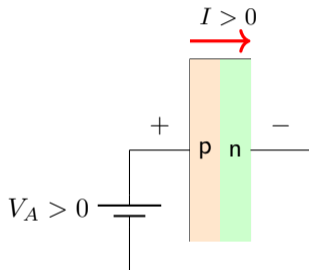
Forward Bias: Circuit Configuration

Definition:

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

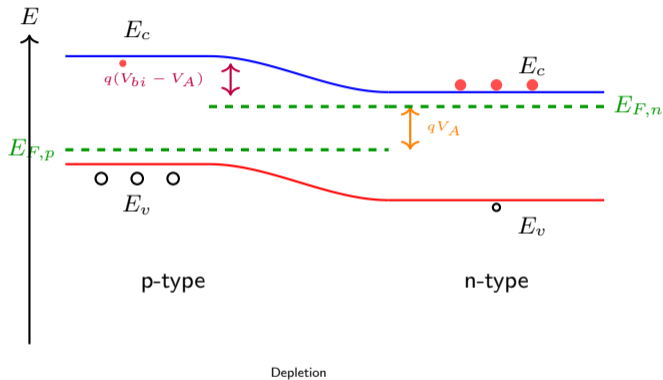
Effect on Junction:

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



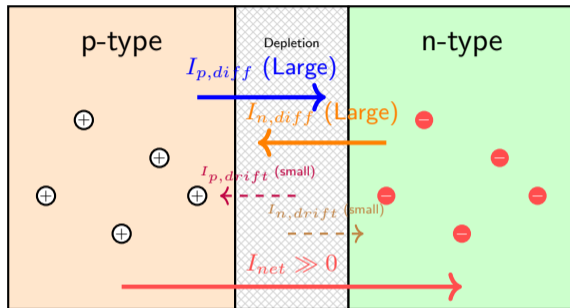
Key Point

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



- **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 $V_A > 0$

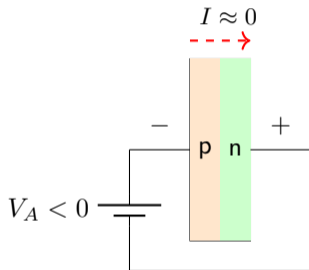
Reverse Bias: Circuit Configuration

Definition:

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

Effect on Junction:

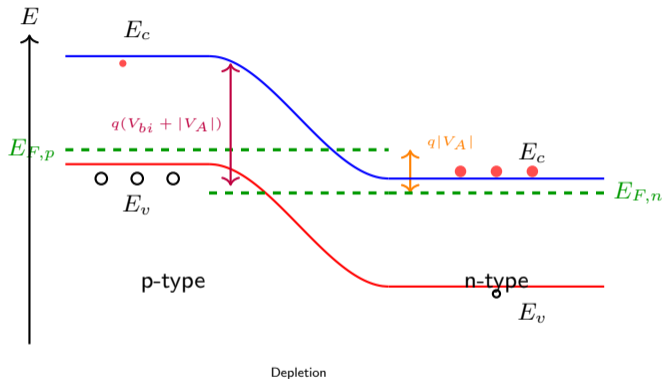
- Increases barrier height
- Barrier becomes:
 $q(V_{bi} - V_A) = q(V_{bi} + |V_A|)$
- Prevents carrier injection
- Very small current (leakage)



Key Point

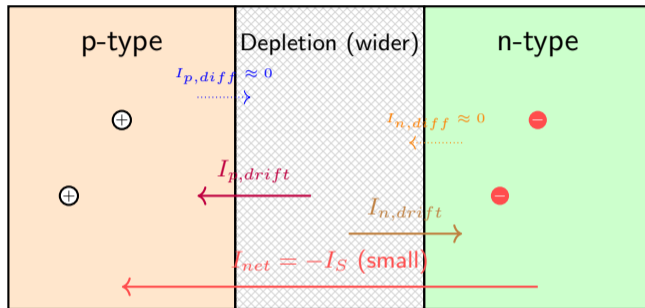
Reverse bias **increases** the potential barrier, preventing majority carrier flow. Only small leakage current flows.

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

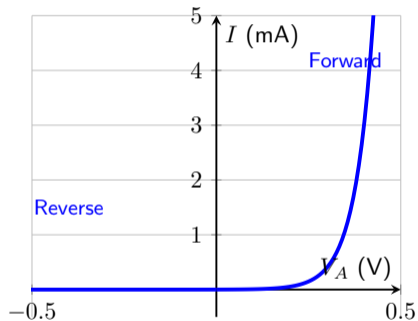
$$I = I_S \left(e^{V_A/V_T} - 1 \right)$$

where:

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

Forward Bias ($V_A > 0$):

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



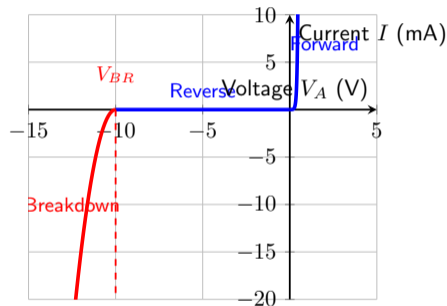
Reverse Bias Breakdown

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} :

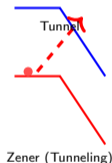
- Voltage at which breakdown occurs
- Depends on doping concentration
- Higher doping \rightarrow lower V_{BR}
- Typical: 50V to 1000V
- Zener diodes: 2V to 200V



Breakdown Mechanisms

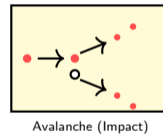
1. Zener Breakdown

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



2. Avalanche Breakdown

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



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	$V_T = \frac{kT}{q} \approx 26 \text{ mV}$
Forward bias	$I \approx I_S e^{V_A/V_T}$
Reverse bias	$I \approx -I_S$

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

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