

# 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

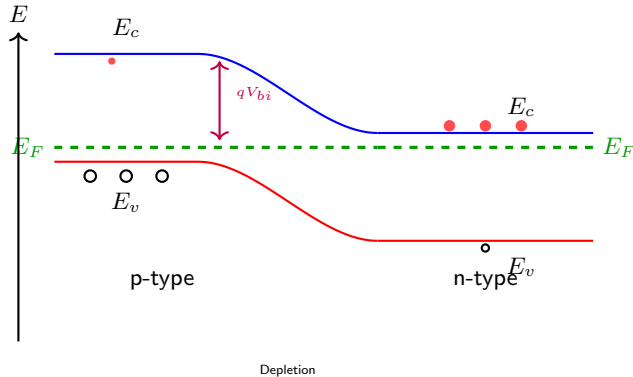
## Lecture Objectives

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

## Applications:

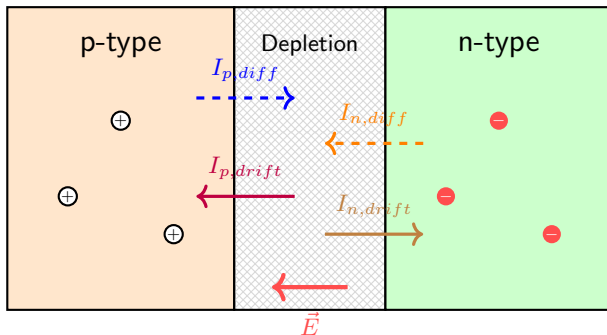
- Rectifier circuits
- Voltage regulation (Zener diodes)
- Switching circuits
- Power supplies

# 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 ( $V_A = \text{open circuit}$ )

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

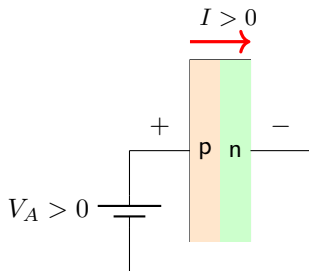
# Forward Bias: Circuit Configuration

## Definition:

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

## Effect on Junction:

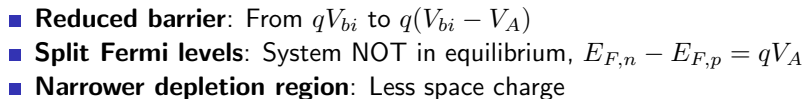
- Reduces barrier height
- Barrier becomes:  $q(V_{bi} - V_A)$
- Increases carrier injection
- Large current flows



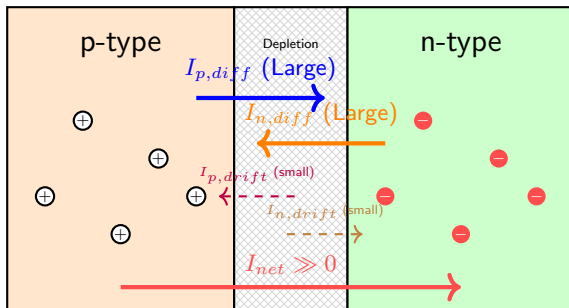
## Key Point

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

## PN Junction Under Bias



# 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  $V_A > 0$

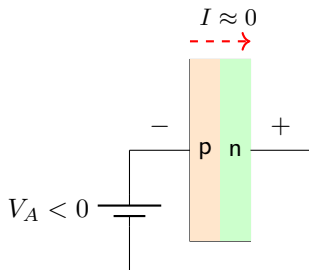
# Reverse Bias: Circuit Configuration

## 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)

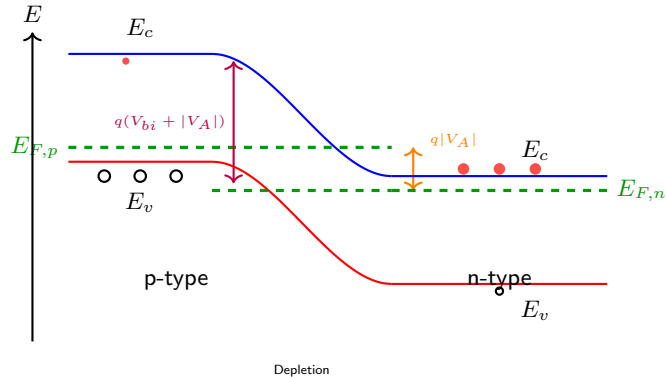


## Key Point

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

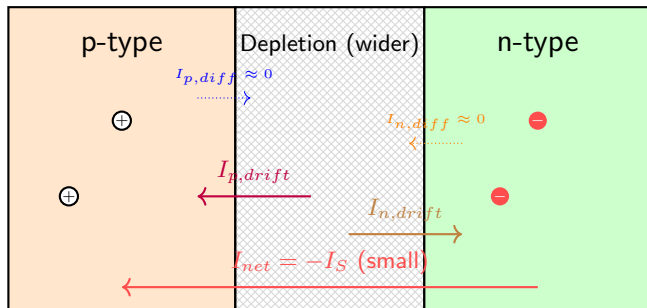


# Reverse Bias: Energy Band Diagram



- **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

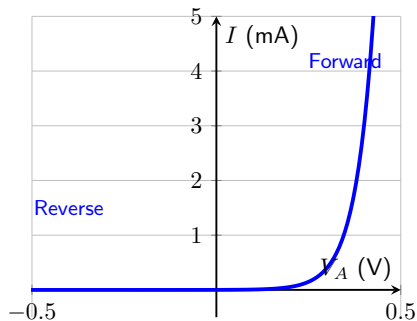
$$I = I_S \left( e^{V_A/V_T} - 1 \right)$$

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** ( $V_A > 0$ ):

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



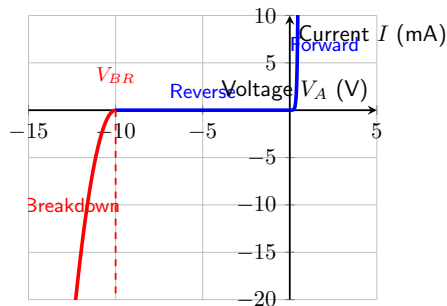
# Reverse Bias Breakdown

## 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 $V_{BR}$ :

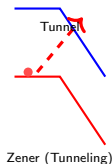
- Voltage at which breakdown occurs
- Depends on doping concentration
- Higher doping  $\rightarrow$  lower  $V_{BR}$
- Typical: 50V to 1000V
- Zener diodes: 2V to 200V



# Breakdown Mechanisms

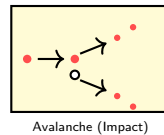
## 1. Zener Breakdown

- 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