Introduction to Semiconductor Physics

Crystal Structure, Energy Bands, and Doping

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Spring 2026

Why Study Semiconductors?

Foundation of Modern Electronics:

- Diodes, transistors, and integrated circuits
- Between conductors and insulators
- Controllable electrical properties

Key Questions:

- What makes silicon special?
- How do electrons move in semiconductors?
- What are energy bands?
- How does doping change conductivity?

Applications:

- Microprocessors and memory
- Sensors and photodetectors
- Power electronics
- RF and communication devices

Lecture Objectives

- Understand crystal structure
- Learn about energy bands
- Explore intrinsic vs extrinsic semiconductors
- Understand n-type and p-type doping

Types of Materials by Conductivity

Material	Resistivity (Ω·m)	Band Gap (eV)	Examples
Conductors	10^{-8} to 10^{-6}	0	Copper, Aluminum, Gold
Semiconductors	10^{-5} to 10^{3}	0.5 to 3	Silicon, Germanium, GaAs
Insulators	10^{11} to 10^{16}	> 5	Glass, Rubber, Diamond

- **Conductors**: Many free electrons, low resistance
- **Insulators**: Almost no free electrons, very high resistance
- **Semiconductors**: Few free electrons at room temperature, but controllable ('magic rocks')

Silicon Crystal Structure

Semiconductor Physics

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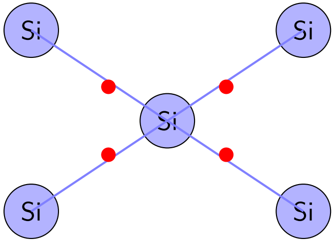
Silicon Atom:

- Atomic number: 14
- 4 valence electrons
- Forms covalent bonds

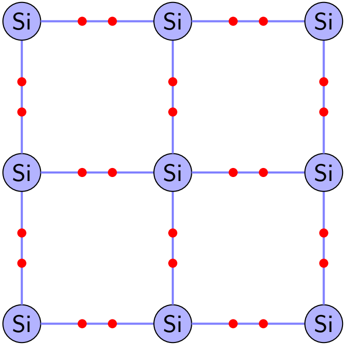
Diamond Lattice:

- Face-centered cubic structure
- Each Si atom bonds with 4 neighbors
- Tetrahedral arrangement
- Very stable at room temperature



Covalent Bonding: Each bond shares 2 electrons

2D Representation of Silicon Lattice



Perfect crystal at 0 K: all electrons in bonds

- At absolute zero (0 K): all valence electrons are bound in covalent bonds
- No free electrons $\Rightarrow$ acts as an insulator at 0 K
- At room temperature: thermal energy breaks some bonds

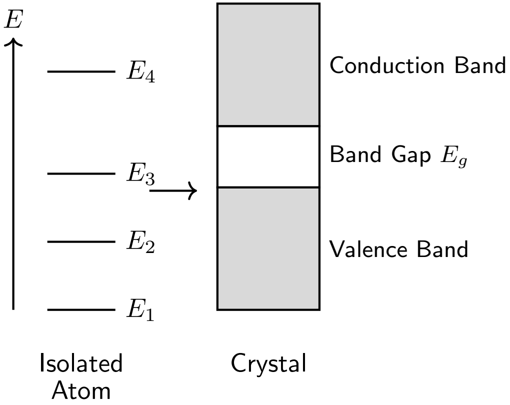
Energy Levels in Atoms vs. Crystals

Isolated Silicon Atom:

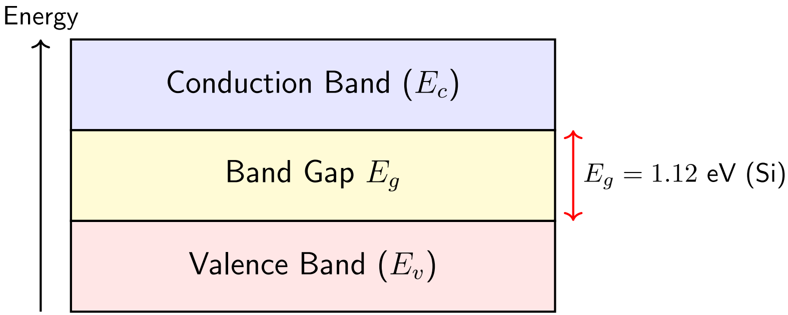
- Discrete energy levels
- 4 valence electrons
- Well-defined orbital energies

Silicon Crystal:

- $\sim 10^{22}$ atoms/cm^3
- Energy levels merge into bands
- Continuous range of energies

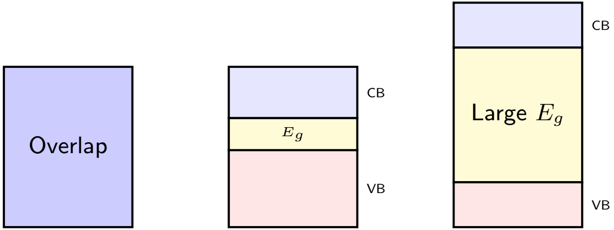


Energy Band Diagram



- **Valence Band**: Energy levels of bonded electrons
- **Conduction Band**: Energy levels of free electrons
- **Band Gap (E_g)**: Energy needed to free an electron from a bond
- For silicon: $E_g = 1.12$ eV at room temperature

Conductors, Semiconductors, and Insulators



Conductor
$E_g = 0$

Semiconductor
$E_g \approx 1$ eV

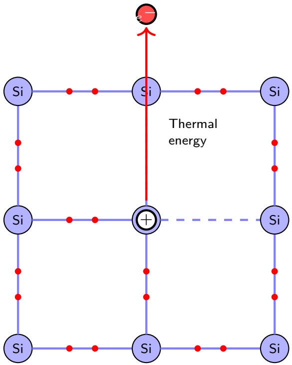
Insulator
$E_g > 5$ eV

- **Conductors**: Bands overlap, electrons flow easily
- **Semiconductors**: Small band gap, thermally activated conduction
- **Insulators**: Large band gap, very few free electrons

Electron-Hole Pair Generation

Thermal Excitation:

- At $T > 0$ K, thermal energy breaks bonds
- Electron 'jumps' from valence band to conduction band
- Leaves behind a **hole** in valence band
- Creates electron-hole pair



Intrinsic Carrier Concentration

$$n_i = p_i \approx 1.5 \times 10^{10} \text{ cm}^{-3}$$

at 300 K for silicon

Holes: Positive Charge Carriers

What is a Hole?

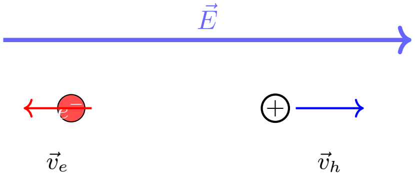
- Absence of electron in covalent bond
- Acts like positive charge carrier
- Can move through crystal
- Real concept, not just theoretical

Hole Motion:

- Adjacent electron fills the hole
- Creates new hole at previous location
- Hole appears to move opposite to electrons

Charge and Current

- **Electron**: charge $= -q$, moves toward $+$
- **Hole**: charge $= +q$, moves toward $-$

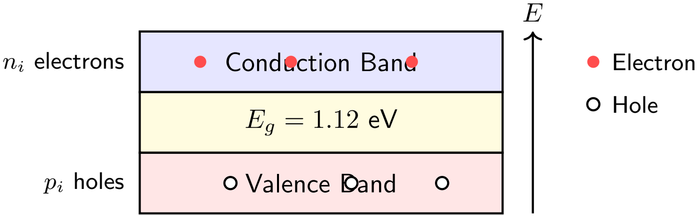


Both contribute to current in same direction!

Intrinsic Semiconductor Properties

Pure (Intrinsic) Semiconductor:

- No impurities added
- Equal number of electrons and holes: $n = p = n_i$
- Low conductivity at room temperature



Mass Action Law

$$n \cdot p = n_i^2$$

Valid for both intrinsic and doped semiconductors at thermal equilibrium

Why Doping?

Problem with Pure Silicon:

- Very low conductivity
- $n_i \approx 10^{10}$ cm^{-3}
- Compare to Si atoms: $\approx 5 \times 10^{22}$ cm^{-3}
- Only 1 in 10^{12} atoms contributes a charge carrier (electrical current)

Solution: Doping

- Add impurity atoms
- Controlled introduction
- Typical: 1 dopant per 10^6 to 10^8 Si atoms
- Increases electrical conductivity

Types of Doping

- **n-type**: Add donors (extra electrons)
- **p-type**: Add acceptors (create holes)

Dopant	Type
Phosphorus (P)	n-type
Arsenic (As)	n-type
Antimony (Sb)	n-type
Boron (B)	p-type
Aluminum (Al)	p-type
Gallium (Ga)	p-type

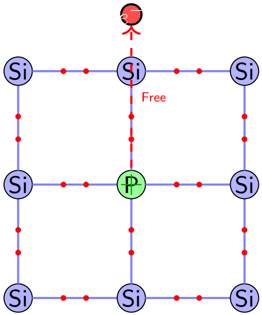
n-Type Semiconductor (Donor Doping)

Adding Phosphorus (P):

- P has 5 valence electrons
- Si has 4 valence electrons
- P substitutes for Si in lattice
- 4 electrons form bonds
- 5th electron is loosely bound
- Easily freed to conduction band

n-Type Properties

- $n \gg p$ (electrons dominate)
- Electrons $=$ majority carriers
- Holes $=$ minority carriers
- $n \approx N_D$ (dopant concentration)

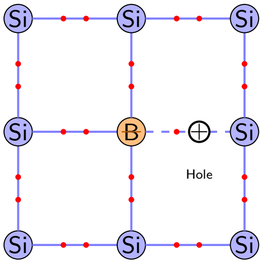


Donor atom donates electron

p-Type Semiconductor (Acceptor Doping)

Adding Boron (B):

- B has 3 valence electrons
- Si has 4 valence electrons
- B substitutes for Si in lattice
- Only 3 electrons available for 4 bonds
- Creates a hole (missing electron)
- Accepts electron from neighboring bond



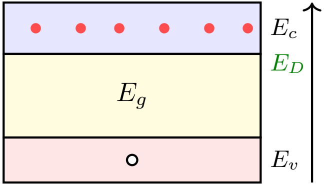
Acceptor atom accepts electron (creates hole)

p-Type Properties

- $p \gg n$ (holes dominate)
- Holes $=$ majority carriers
- Electrons $=$ minority carriers
- $p \approx N_A$ (dopant concentration)

Energy Band Diagram: Doped Semiconductors

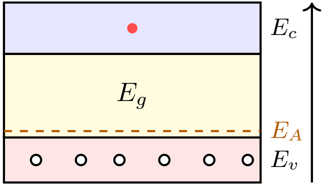
n-Type:



$n \gg p$

- Donor level near E_c
- Easy to ionize donors
- Many electrons in CB

p-Type:



$p \gg n$

- Acceptor level near E_v
- Easy to ionize acceptors
- Many holes in VB

Two Mechanisms of Current Flow

1. **Drift Current**:
   - Caused by electric field
   - Electrons drift opposite to field, holes drift with field
   - $J_{drift} = q(n\mu_n + p\mu_p)E$
   - μ_n, μ_p are electron and hole mobilities
2. **Diffusion Current**:
   - Caused by concentration gradient
   - Carriers move from high to low concentration
   - $J_{diff,n} = qD_n \frac{dn}{dx}, \quad J_{diff,p} = -qD_p \frac{dp}{dx}$
   - D_n, D_p are diffusion constants

Total Current

$$J_{total} = J_{drift} + J_{diffusion}$$

Both mechanisms important in semiconductor devices (especially pn junctions)

Conductivity of Doped Semiconductors

Conductivity Formula:

$$\sigma = q(n\mu_n + p\mu_p)$$

n-Type:

- $n \approx N_D$ (donor concentration)
- $p \ll n$ (minority carriers)
- $\sigma \approx qN_D\mu_n$
- Conductivity dominated by electrons

p-Type:

- $p \approx N_A$ (acceptor concentration)
- $n \ll p$ (minority carriers)
- $\sigma \approx qN_A\mu_p$
- Conductivity dominated by holes

Example: $N_D = 10^{16}$ cm^{-3}

- 1,000,000 times more carriers than the intrinsic semiconductor
- Much higher conductivity

Mass Action Law still holds:

$$n \cdot p = n_i^2$$

For n-type: $p = \frac{n_i^2}{N_D}$

For p-type: $n = \frac{n_i^2}{N_A}$

Typical Doping Concentrations

Type	**Concentration (cm^{-3})**	**Application**
Intrinsic Si	$n_i = 1.5 \times 10^{10}$	Reference
Lightly doped	10^{14} - 10^{16}	Base regions, substrates
Moderately doped	10^{16} - 10^{18}	Emitter, collector regions
Heavily doped	10^{18} - 10^{20}	Contacts, low-resistance paths

- Silicon has $\approx 5 \times 10^{22}$ atoms/cm^3
- Even "heavy" doping is only $\approx$ 1 dopant per 1000 Si atoms
- Precise control needed for device fabrication
- Ion implantation and diffusion are common doping techniques

Key Formulas Reference

Parameter	Formula
Intrinsic carrier conc.	$n_i \approx 1.5 \times 10^{10}$ cm^{-3}
Mass action law	$n \cdot p = n_i^2$
n-type majority	$n \approx N_D$
n-type minority	$p \approx \frac{n_i^2}{N_D}$

Parameter	Formula
p-type majority	$p \approx N_A$
p-type minority	$n \approx \frac{n_i^2}{N_A}$
Conductivity	$\sigma = q(n\mu_n + p\mu_p)$
Drift current density	$J = \sigma E$

Summary: Semiconductor Fundamentals

1. **Crystal Structure**:
   - Silicon forms diamond lattice with covalent bonds
   - 4 valence electrons per atom
2. **Energy Bands**:
   - Valence band (bonded electrons) and conduction band (free electrons)
   - Band gap $E_g = 1.12$ eV for silicon
   - Thermal energy creates electron-hole pairs
3. **Doping**:
   - n-type: donor atoms (P, As) provide extra electrons
   - p-type: acceptor atoms (B, Al) create holes
   - Dramatically increases conductivity
4. **Current Mechanisms**:
   - Drift (electric field) and diffusion (concentration gradient)
   - Both important in devices