Course Optoelectronic

Parcours électronique S6
2025-2026

Pr. Omar EL OUTASSI

Syllabus

- Students are invited to respect the schedules of the TD courses and practical work
- Mobile phones must be turned off during the TD and Practical Work course sessions
- The course is presented in PowerPoint with image illustrations and if necessary by video
- The examination period is scheduled within fixed deadlines

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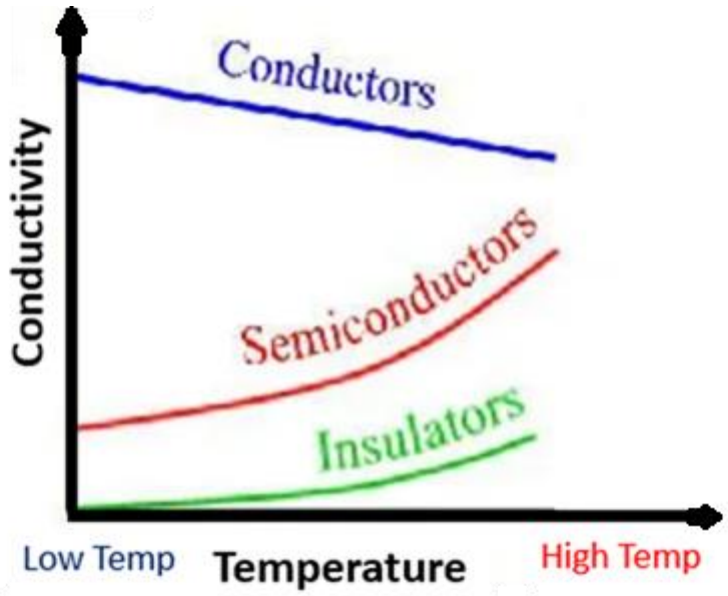
Chapitre 1: Semiconductors

- Describe semiconductors
- Explain the types of semiconductors
- Define semiconductor alloys
- Explain the formation and recombination of electron-hole pairs
- Elucidate energy bands in solids

What Are Semiconductors?

- **Conditional Conductivity:** Materials that conduct electricity only under specific conditions, acting as a middle ground between conductors and insulators.
- **Temperature Response:** Unlike metals, semiconductor resistivity **decreases** as temperature **increases**.
- **Environmental Sensitivity:** Highly reactive to both **heat** and **light**.
- **Essential Components:** The foundational material used to build **Integrated Circuits (ICs)**, **transistors**, and **diodes**.



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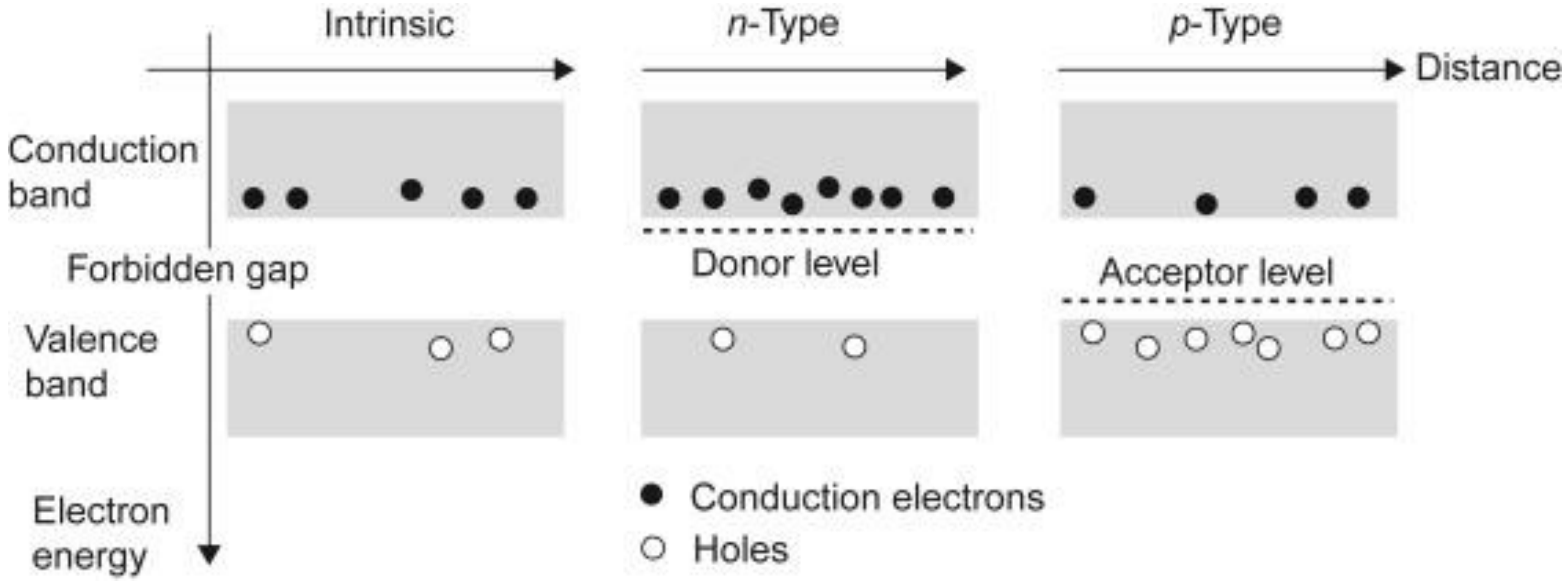
Charge Carriers: Electrons and Holes

➢ Fundamentals:

- Electrons and holes are the two types of **charge carriers** in semiconductors.



- Their movement through the crystal lattice results in the flow of electric current.

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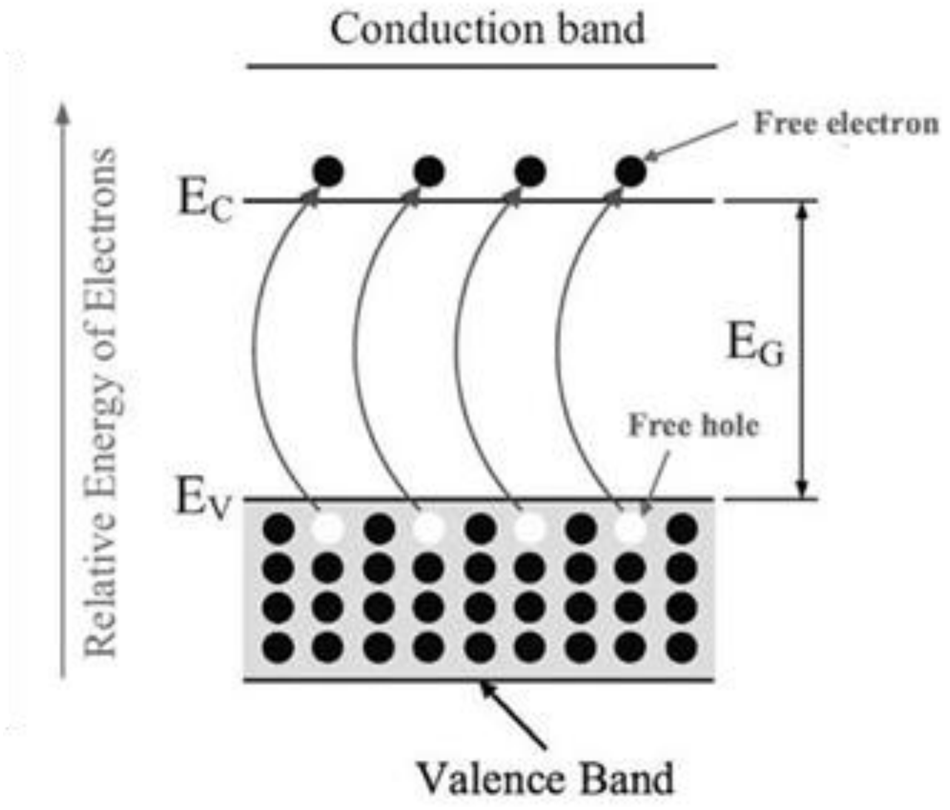
Charge Carriers: Electrons and Holes

- **Electrons (Negative Charge):**
  - Primary carriers of electric charge in semiconductors.
  - **Valence Band:** Electrons are "bound" to atoms and contribute little to current.
  - **Conduction Band:** Once electrons gain energy, they become "free" and move throughout the material.



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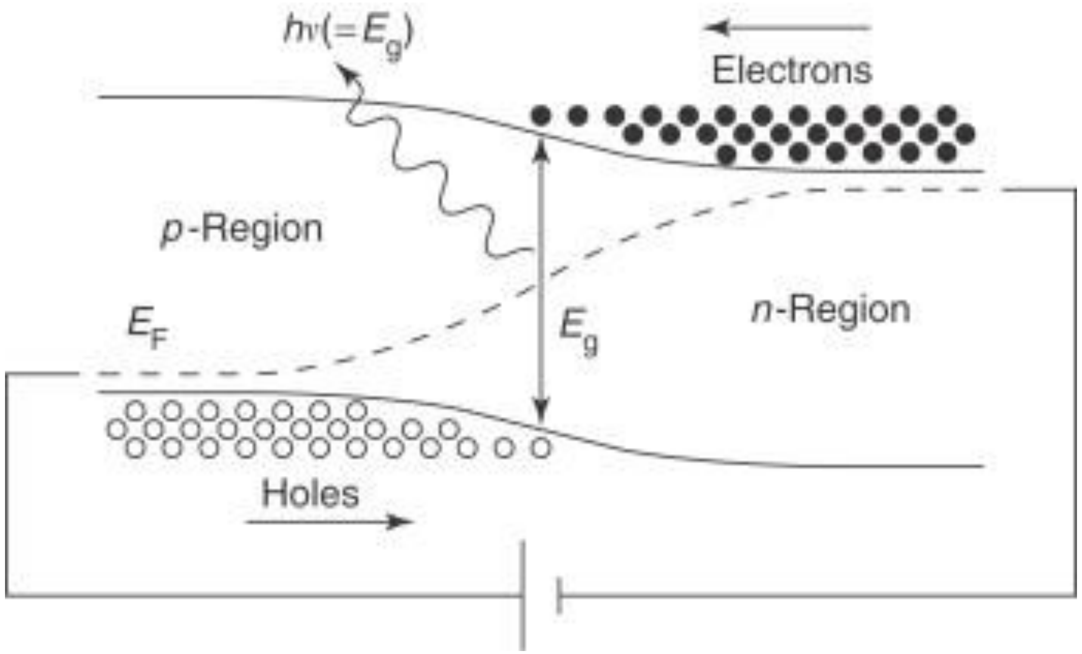
Charge Carriers: Electrons and Holes

- **Holes (Positive Charge):**
  - **Definition:** A hole is a vacant spot left behind in the valence band when an electron gains energy and moves to the conduction band.



  - **Nature:** Represents a region of positive charge created by the absence of a negative electron in a covalent bond.
  - **Mechanism:** Holes act as mobile positive charge carriers as neighboring valence electrons move to fill the empty "openings.“

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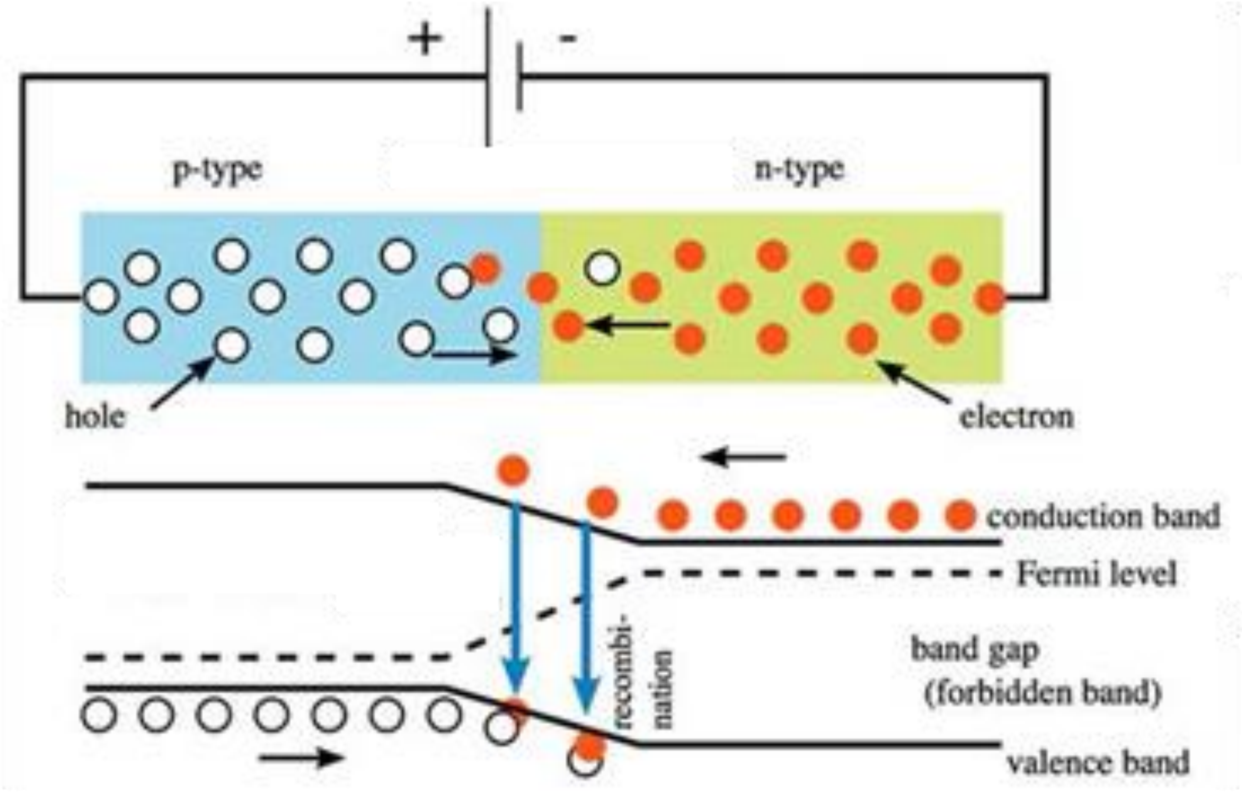
Charge Carriers: Electrons and Holes

- **Key Concept:** Current in semiconductors is the dual flow of **free electrons** in the conduction band and **holes** in the valence band.



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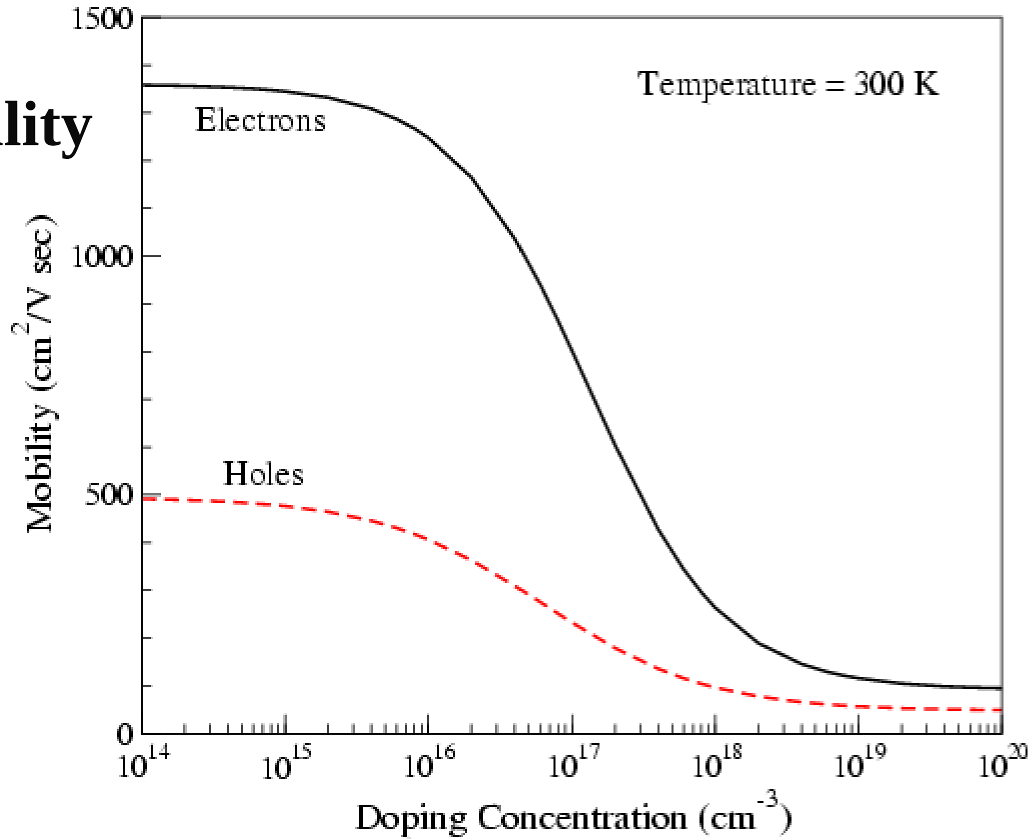
Mobility of Electrons and Holes

➢ Mobility Gap:

- In semiconductors like Silicon, **electron mobility is significantly higher** than hole mobility.
- This difference is rooted in how each carrier moves through the material's atomic structure.



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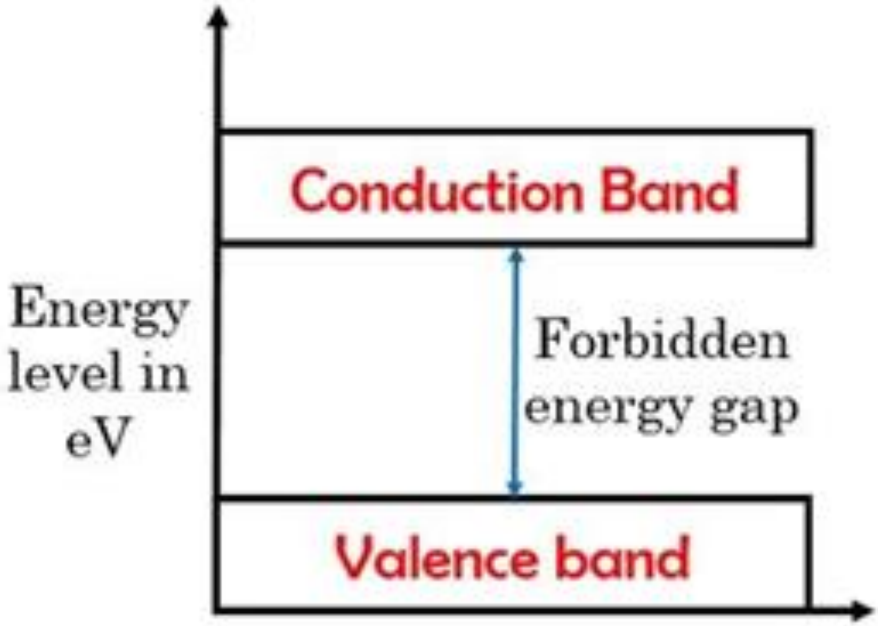
Mobility of Electrons and Holes

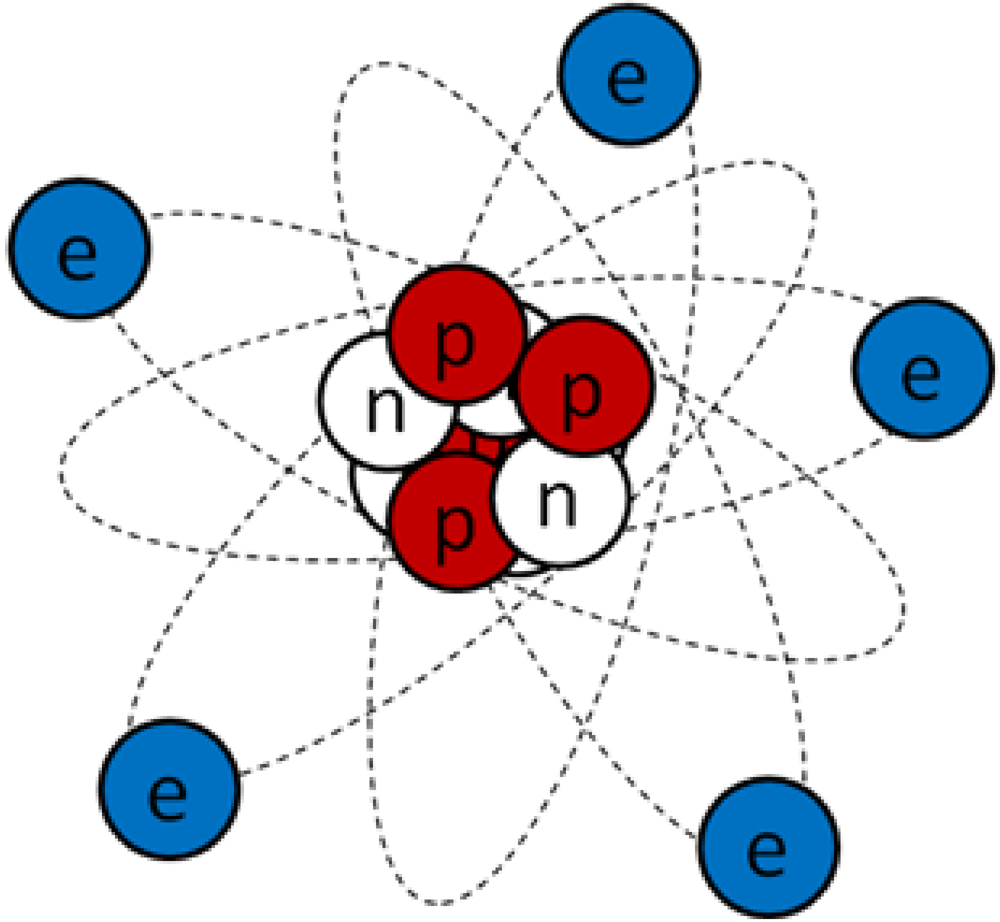
- **Conduction vs. Valence Band:**
  - **Electrons:** Reside in the **Conduction Band**, where they move with greater freedom and fewer burdens.



  - **Holes:** Reside and move within the **Valence Band**. Their movement is more restricted as it requires the constant breaking and reforming of covalent bonds.

Mobility of Electrons and Holes

- **Interaction with Atomic Nuclei:**
  - **Negative Electrons:** Experience relatively less resistance from the positively charged atomic nuclei as they traverse the lattice.
  - **Positive Holes:** Encounter stronger **electrostatic repulsion** from the positively charged nuclei, which further slows their effective movement.



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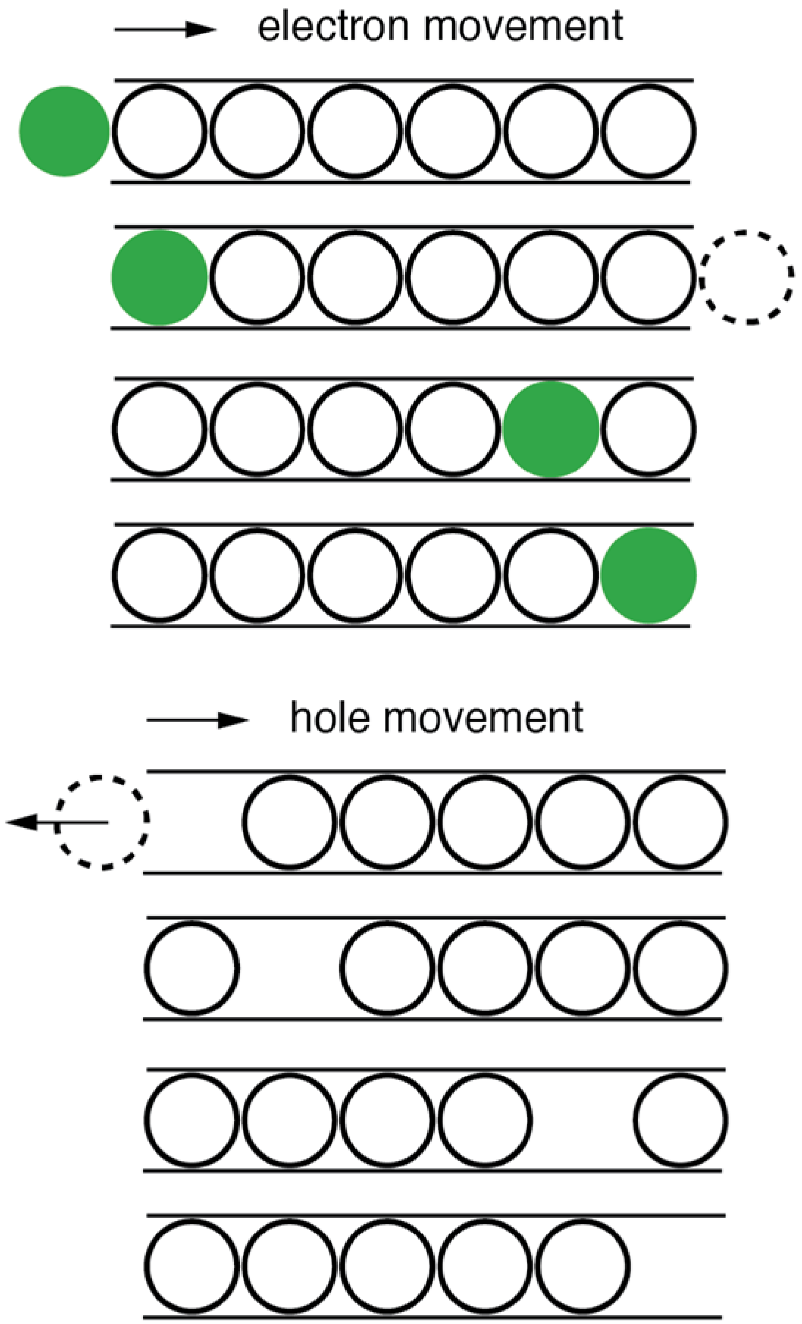
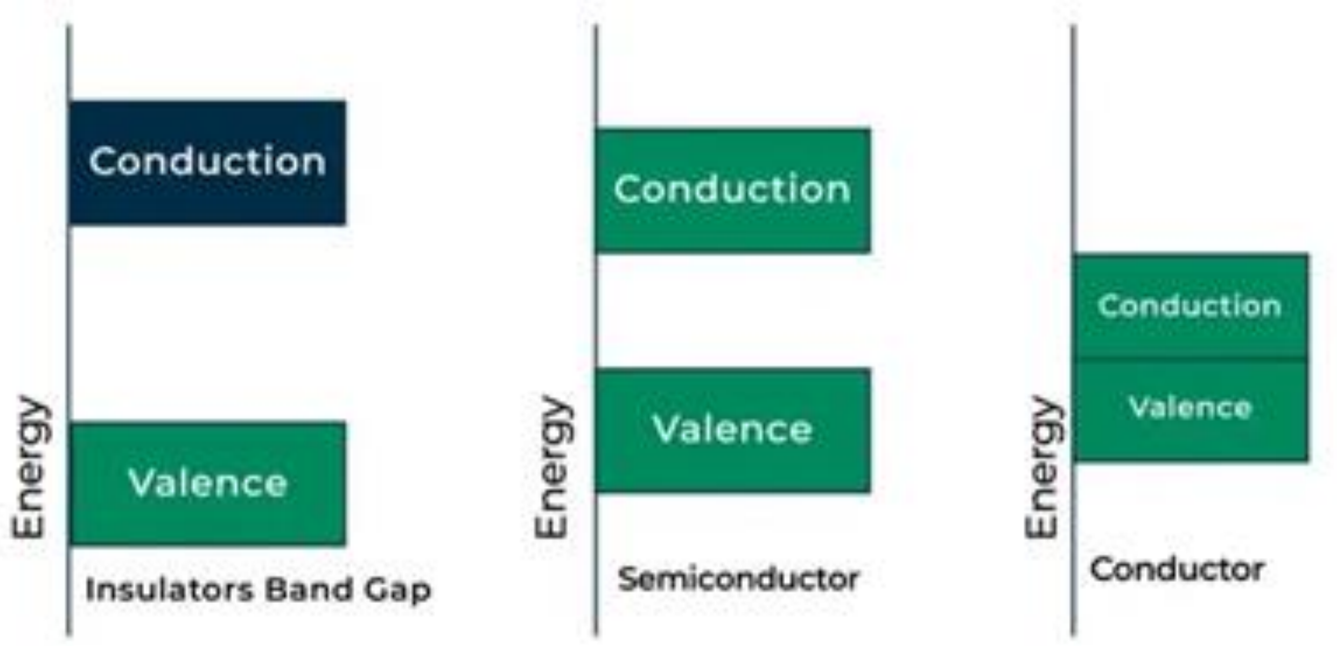
Mobility of Electrons and Holes

- **Engineering Impact:**
  - Because electrons move faster than holes, N-type materials and electron-based devices (like N-MOS transistors) generally offer higher switching speeds and better performance in high-frequency applications.
  - In the given Silicon Bond Model, when a free electron moves from its lattice position, it leaves behind a hole with an opposite charge. These holes act as positive charge carriers within the lattice.



Band Theory of Semiconductors

- **Visualizing the Band Gap:**



- Band theory explains the conductivity of materials based on the "energy gap" between the **Valence Band** and the **Conduction Band**.
- This gap determines how much energy an electron needs to become a mobile charge carrier.

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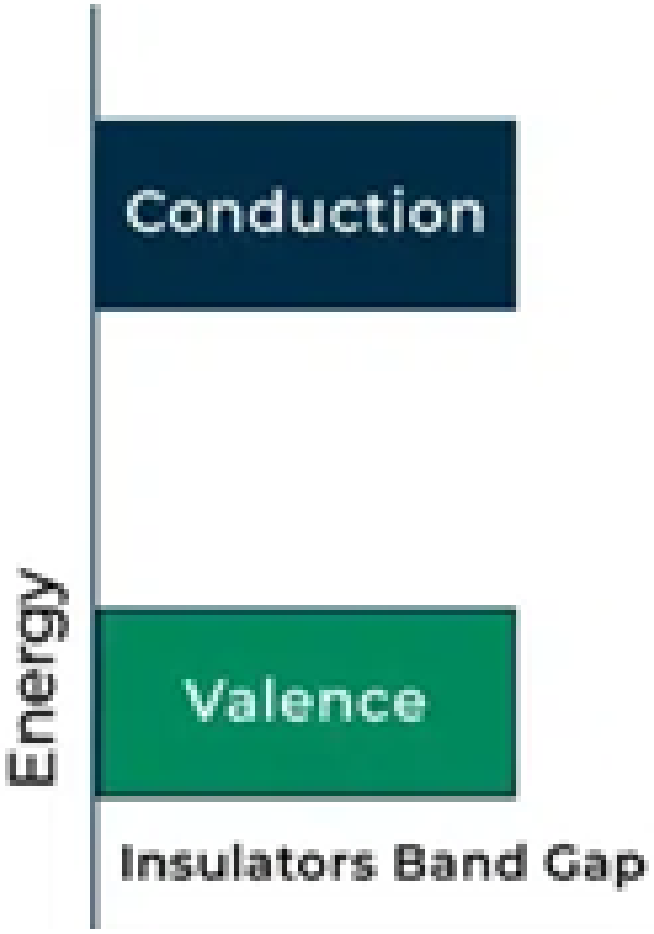
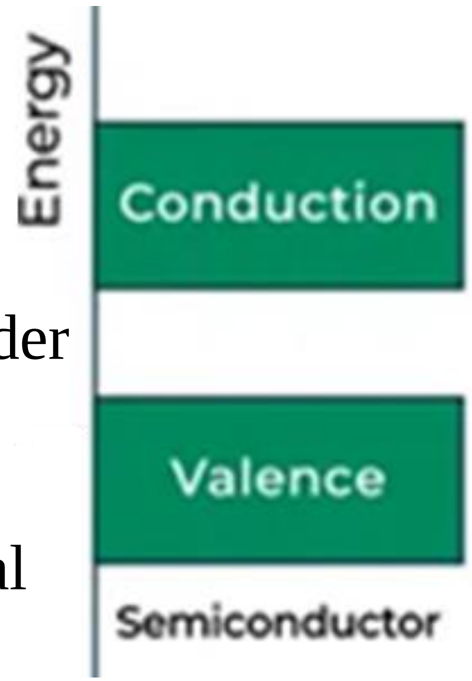
Band Theory of Semiconductors

- **Insulators (The Largest Gap):**
  - Possess the highest energy gap between bands.
  - **Mechanism:** Even with applied energy, electrons cannot bridge the wide gap to move from the valence to the conduction band.
  - **Result:** Electrical conduction is not possible under normal conditions.



Band Theory of Semiconductors

- **Semiconductors (The Intermediate Gap):**
  - The energy gap falls between that of a conductor and an insulator.
  - **Conductivity:** They do not conduct electricity at absolute zero or under "normal" base conditions without external excitation.
  - **Activation:** By supplying specific energy (thermal or electrical) equal to the **band gap**, electrons can be moved into the conduction band to allow current flow.



- **Key Distinction:**
  - Unlike insulators, the semiconductor gap is small enough that external energy can "switch" the material from a non-conducting to a conducting state.

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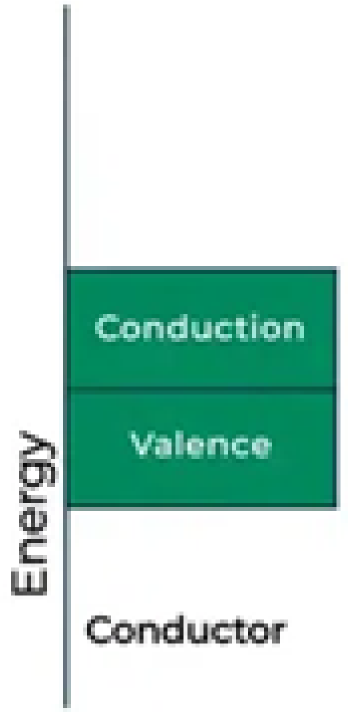
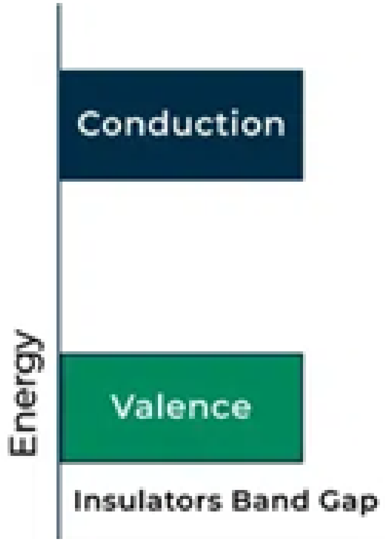
Valence and Conduction Bands

- **Valence Band (VB):**
  - The highest range of energy levels normally occupied by electrons.
  - In semiconductors, the **small band gap** allows these valence electrons to be excited and jump to the conduction band when external energy (heat/light) is applied.
- **Conduction Band (CB):**
  - Situated **above** the valence band (separated by the energy gap).
  - Consists of energy levels that accommodate mobile charge carriers: **free electrons** and **holes**.
  - In semiconductors, this band is nearly empty until it "accepts" electrons that have jumped up from the valence band.

Valence and Conduction Bands

- **Comparison with Conductors:**
  - In conductors (metals), there is **no band gap**; the valence and conduction bands are overlapped or "collapsed."
  - **Result:** No external energy is required for conduction, as electrons are inherently free to move.
- **Comparison with Insulators:**
  - Insulators have a very wide band gap, making it nearly impossible for electrons to reach the conduction band, regardless of applied energy.





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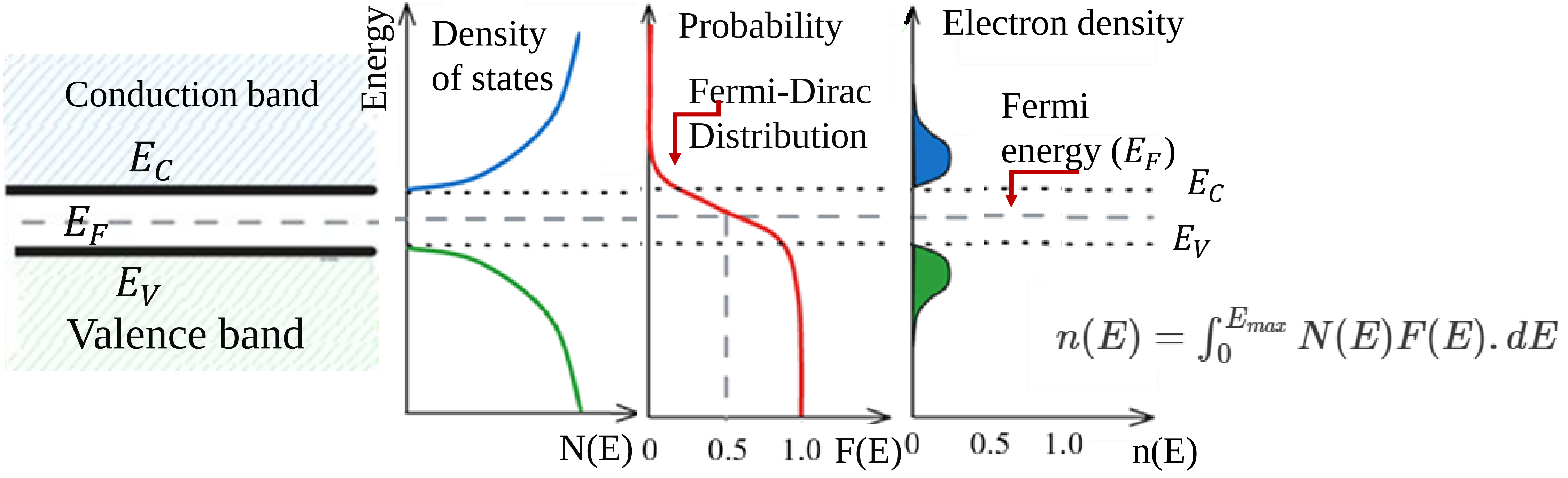
Fermi Level in Semiconductors

- **Definition:** The energy level within the band gap where the probability of finding an electron is exactly **50%**.



Fermi Level in Semiconductors

- **Fermi-Dirac Distribution Function**

The fundamental equation describing the probability F(E) that an available energy state E is occupied by an electron at absolute temperature T is:

$$\mathsf{F}(E) = \frac{1}{1+e^{(E-E_F)/KT}}$$

E_F: Fermi level energy.

K=$1.3810^{-23}\,J/K$: Boltzmann constant

T: Temperature in Kelvin.

Verification: If $E = E_F$

F(E)=1/(1+1)=1/2 (50% probability).

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Fermi Level in Semiconductors

➢ Temperature Dependence:

The intrinsic Fermi level, denoted as E_{Fi} , is expressed as:

$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{3}{4} KT ln\left(\frac{m_h^*}{m_e^*}\right)$$

E_C **:** Energy at the bottom of the conduction band.

E_V **:** Energy at the top of the valence band.

K **:** Boltzmann constant.

T **:** Absolute temperature (in Kelvin).

(m_h^*/m_e^*)**:** Ratio of effective mass of holes to electrons.

Fermi Level in Semiconductors

- **Temperature Dependence:**
  - **At Absolute Zero (0 K):** In an intrinsic semiconductor, the Fermi level sits at the top of the valence band.

At Absolute Zero (0 K)

$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{3}{4} K.0.ln\left(\frac{m_h^*}{m_e^*}\right) = \frac{E_C + E_V}{2}$$

As $T \rightarrow 0K$,

- **Position:** The Fermi level is located **exactly in the middle** of the forbidden bandgap.
- **Conductivity:** Because the thermal energy is zero, no electrons can jump to the conduction band, leaving the material as a perfect insulator with infinite resistance.

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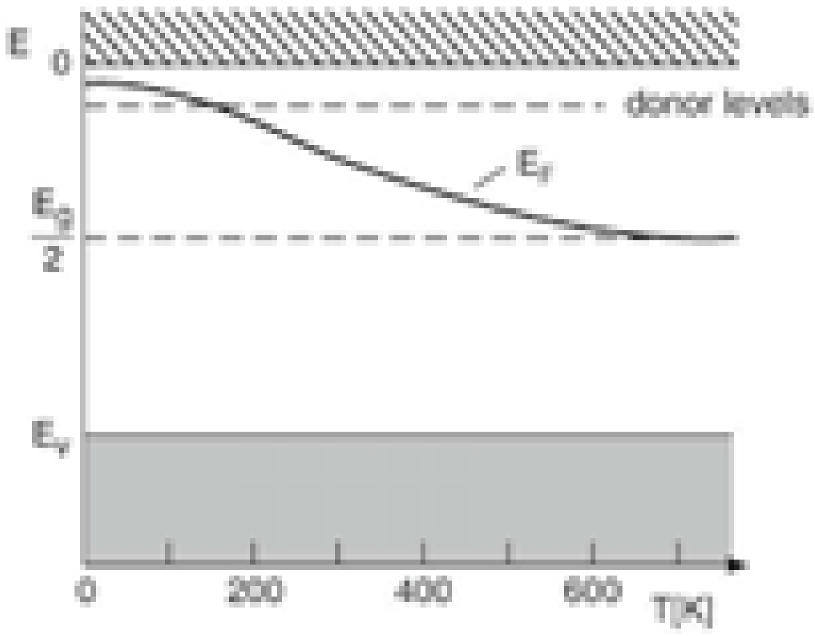
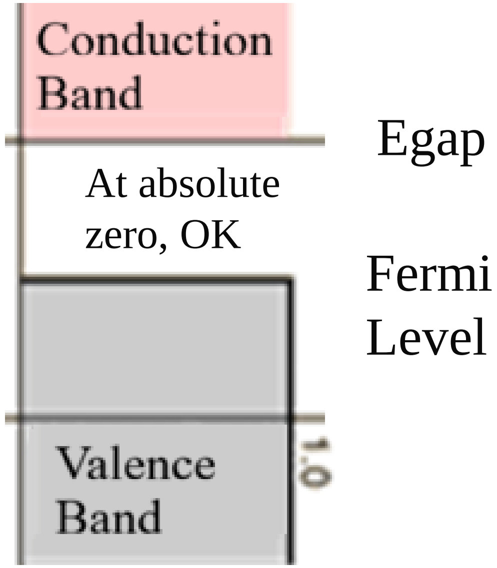
Fermi Level in Semiconductors

- **Temperature Dependence:**
  - **Increasing Temperature:** As thermal energy moves electrons to the conduction band (leaving holes behind), the Fermi level shifts toward the **middle of the band gap**.

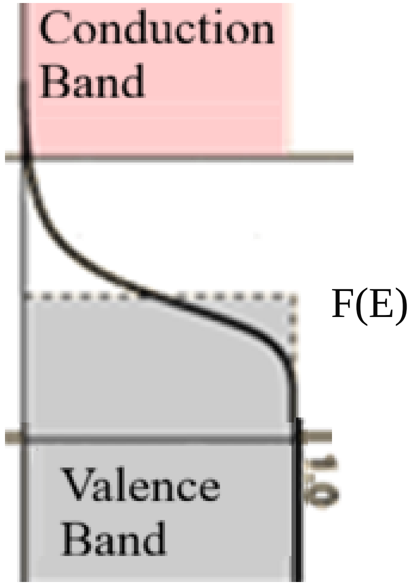


Fermi Level in Semiconductors

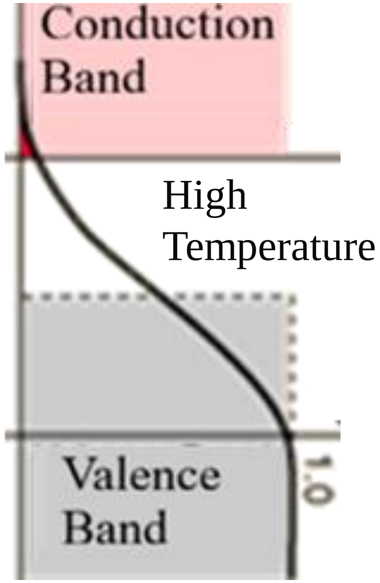
- **Significance:** The position of the Fermi level relative to the energy bands determines the material's conductivity and electronic behavior.



No electrons can be above the valence band at OK, since none have energy above the Fermi level and there are no available energy states in the band gap



Some electrons have energy above the Fermi level Valence Band



At high temperatures, some electrons can reach the conduction band and contribute to electric current

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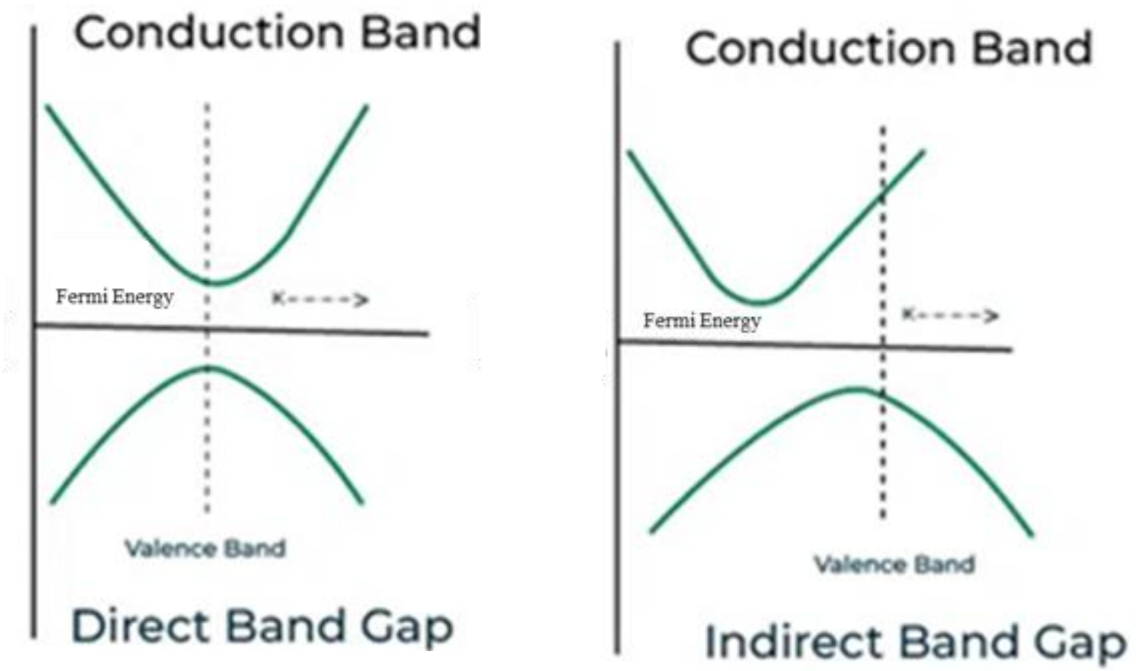
Fermi Level in Semiconductors

Direct vs. Indirect Band Gap Semiconductors

- **Classification:** Semiconductors are categorized based on the alignment of their energy levels in momentum space.



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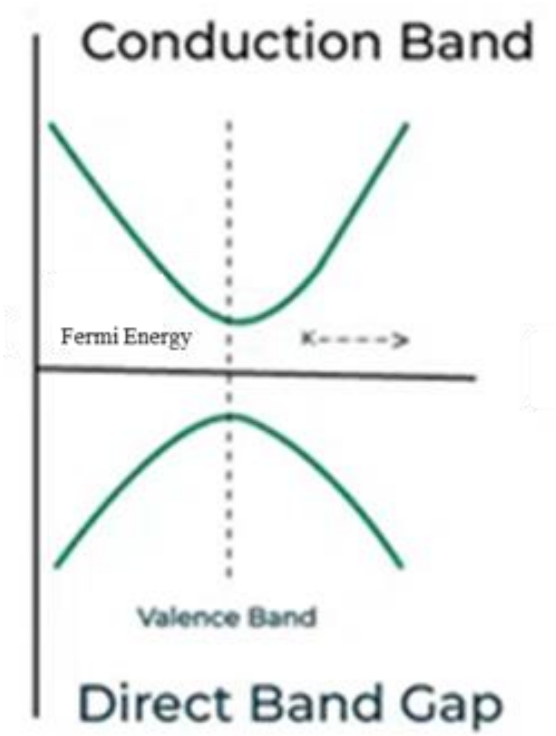
Fermi Level in Semiconductors

Direct vs. Indirect Band Gap Semiconductors

➢ **Direct Band Gap Semiconductors:**

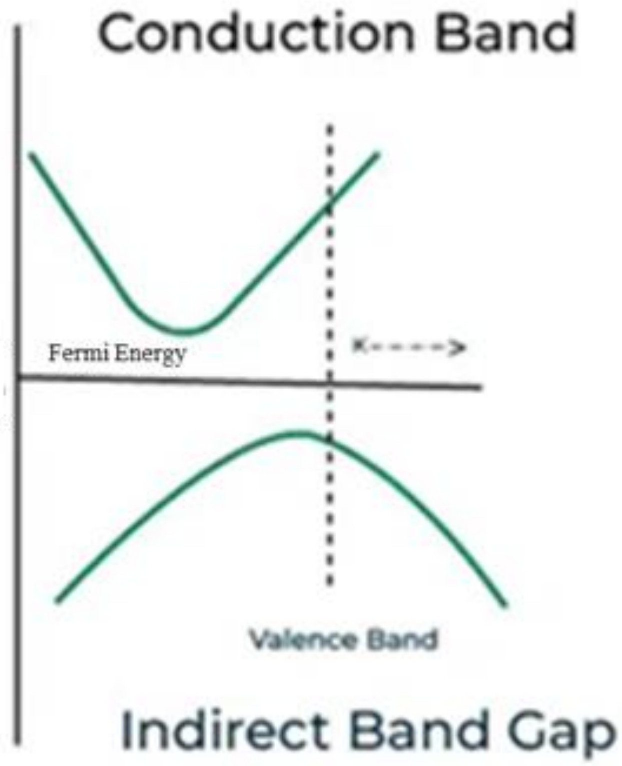
- The maximum energy level of the valence band aligns directly with the minimum energy level of the conduction band.
- **Efficiency:** Electrons can drop from the conduction to the valence band and release energy directly as **light (photons)**.
- **Application:** Essential for LEDs and Laser Diodes (e.g., Gallium Arsenide).



Fermi Level in Semiconductors

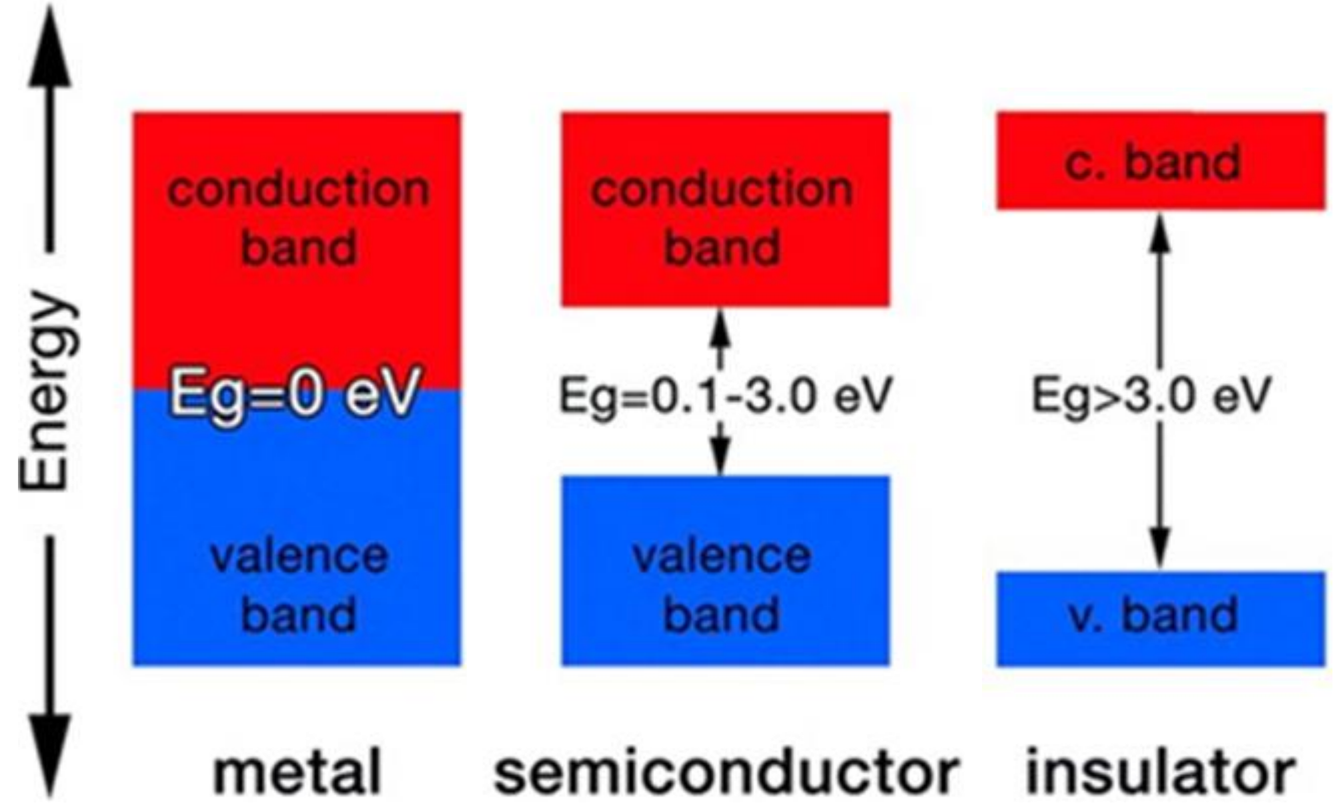
Direct vs. Indirect Band Gap Semiconductors

- **Indirect Band Gap Semiconductors:**
  - The band limits are not aligned; electrons must change momentum to recombine.
  - **Efficiency:** Energy is primarily released as **heat (phonons)** rather than light.
  - **Application:** Common in microprocessors and solar cells (e.g., Silicon).



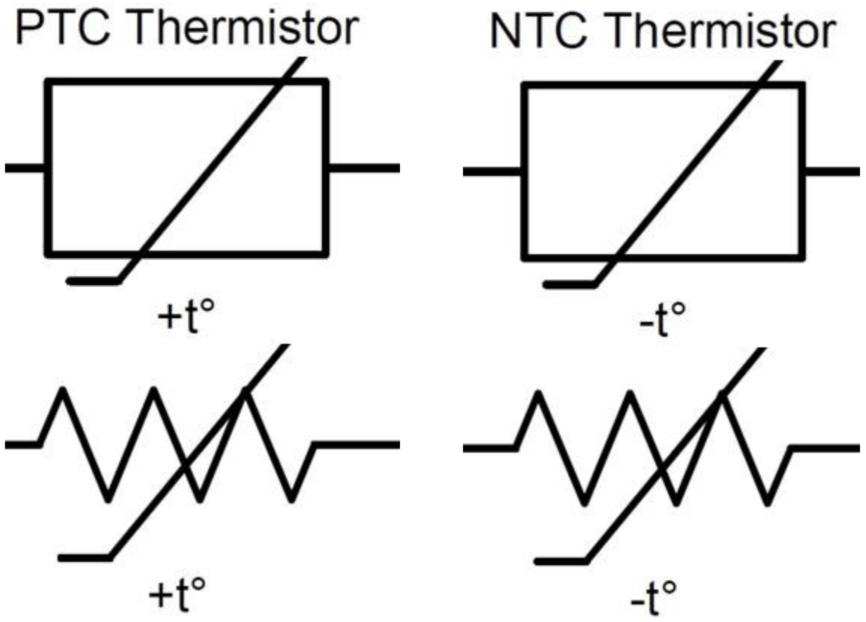
Key Properties of Semiconductors

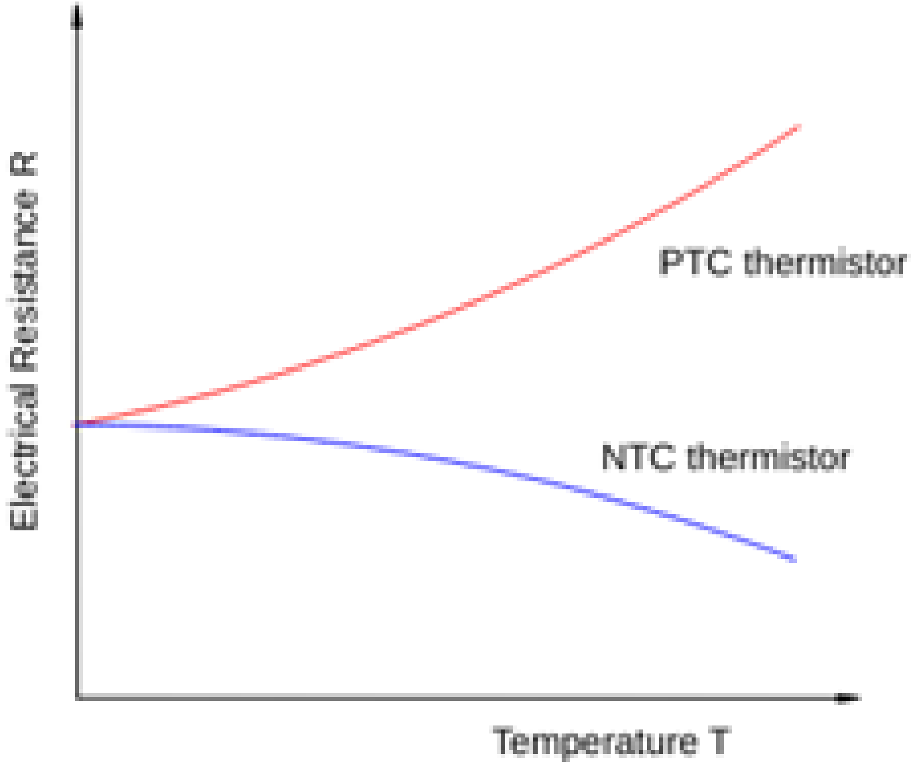
- **Energy Gap (Eg):** The defining range between the valence and conduction bands that determines if a material acts as a conductor or insulator.



Key Properties of Semiconductors

- **Temperature Responsiveness:** Conductivity increases with temperature, making them ideal for **thermistors** and sensors.

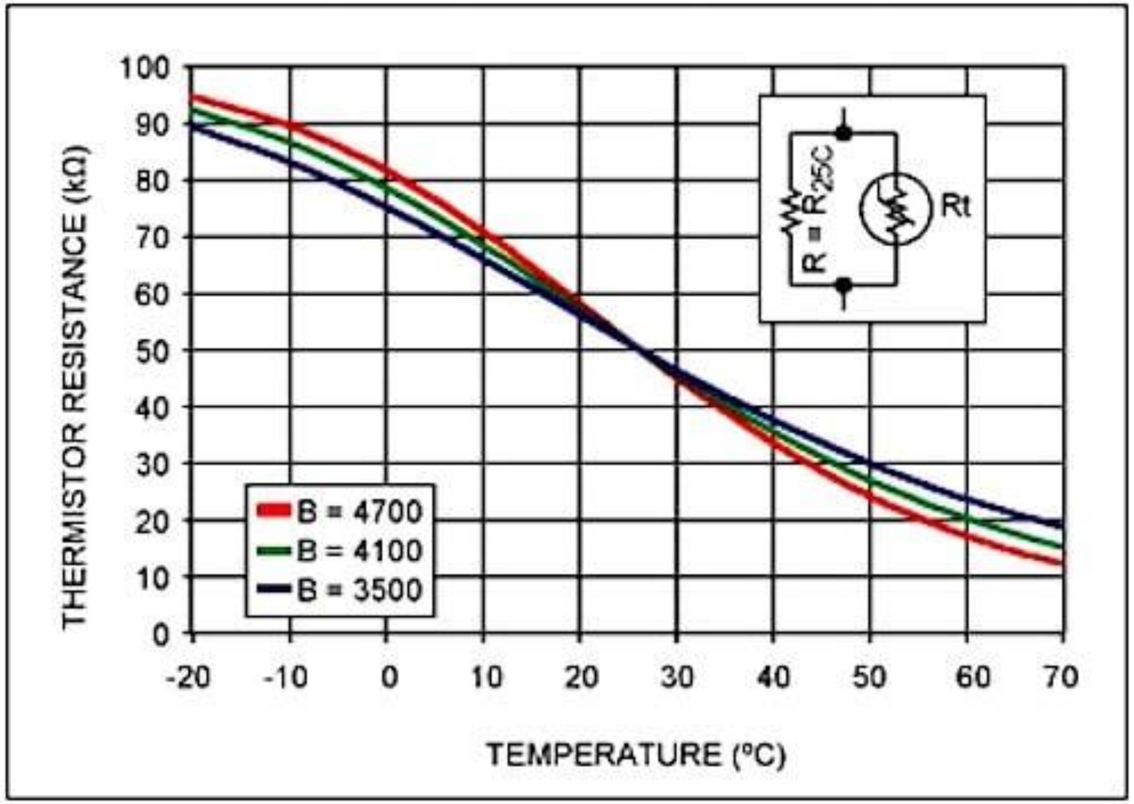


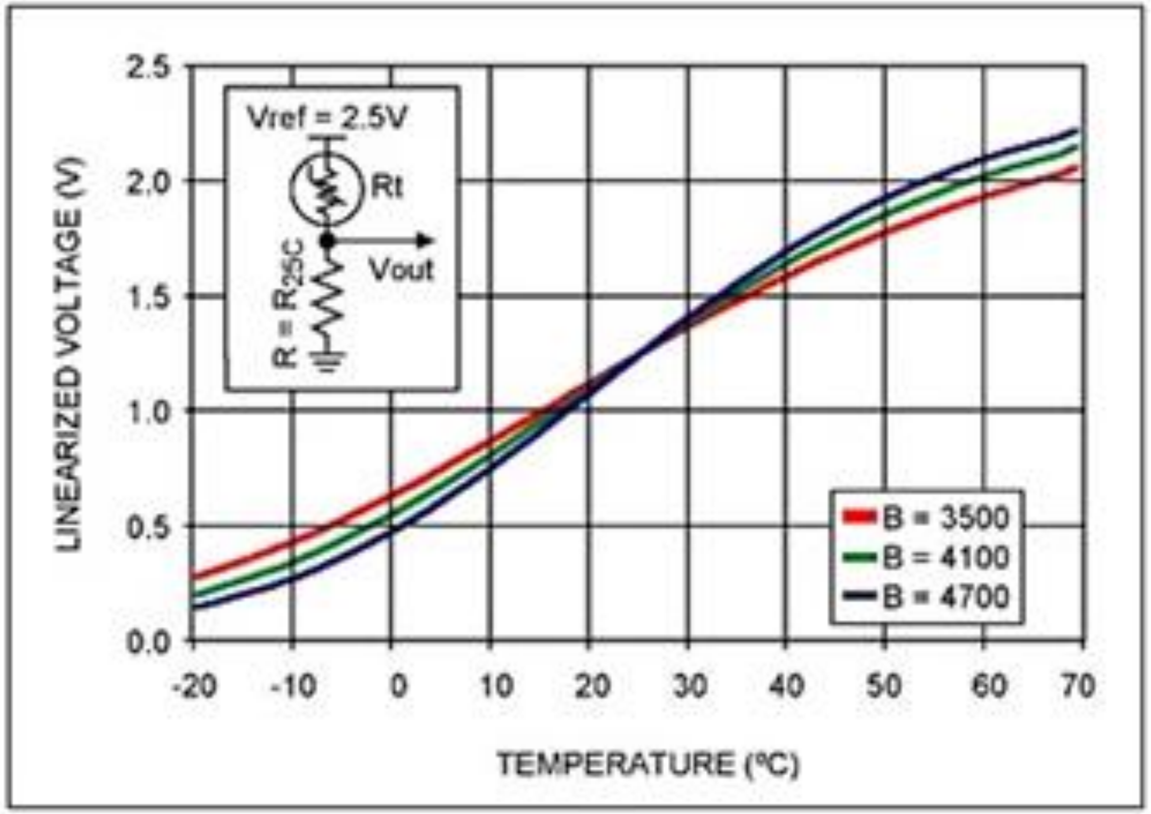


Key Properties of Semiconductors

- **Temperature Responsiveness:**

$$R_T = R_{25C} \cdot e^{\{\beta[(1/(T+273))-(1/298)]\}}$$





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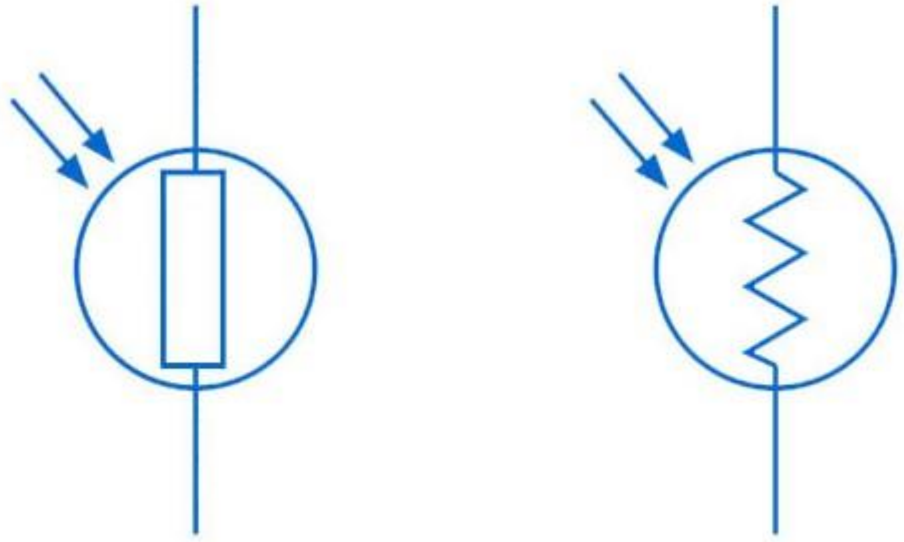
Key Properties of Semiconductors

- **Light Sensitivity:** Exposure to light increases conductivity, a property exploited in **photodetectors** and **solar cells**.



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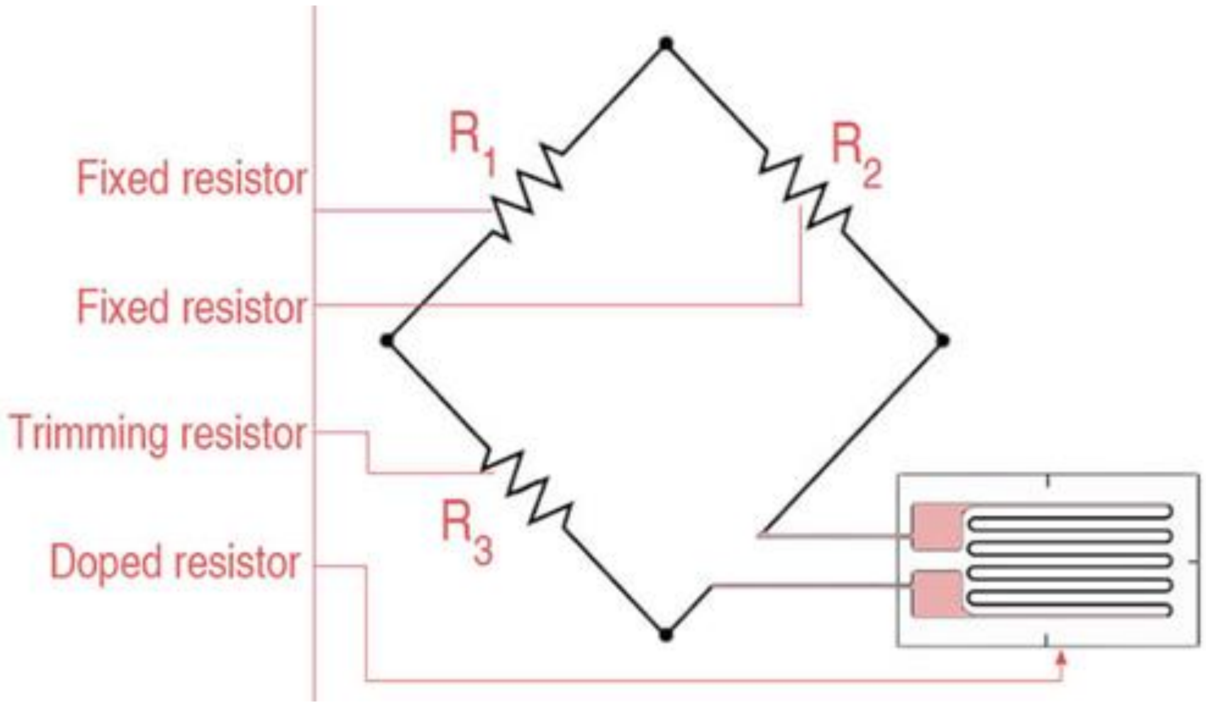
Key Properties of Semiconductors

- **Mechanical Influence:** Through **piezo-resistivity**, resistance changes under mechanical stress, useful in pressure sensors and strain gauges.



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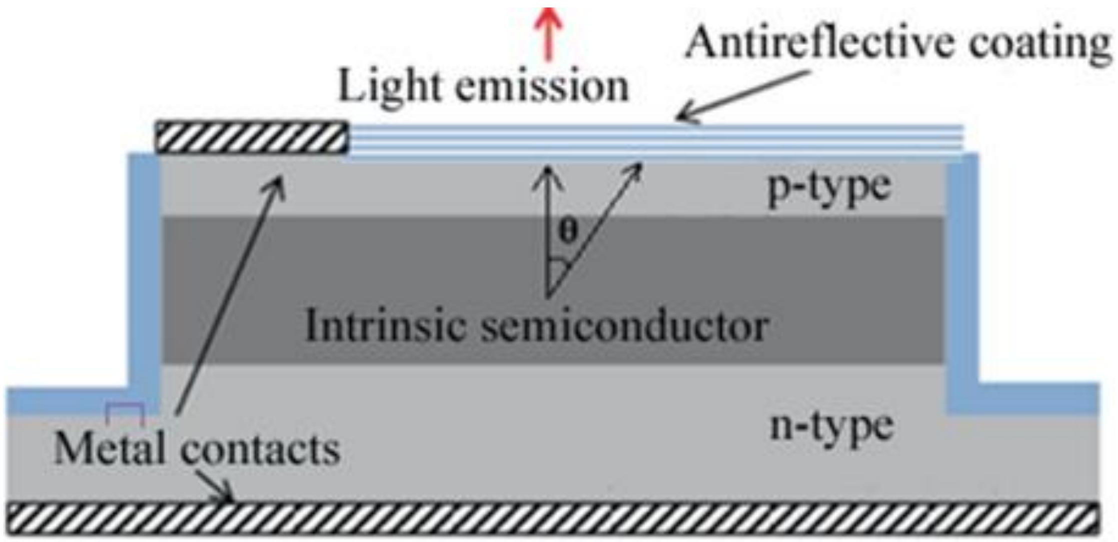
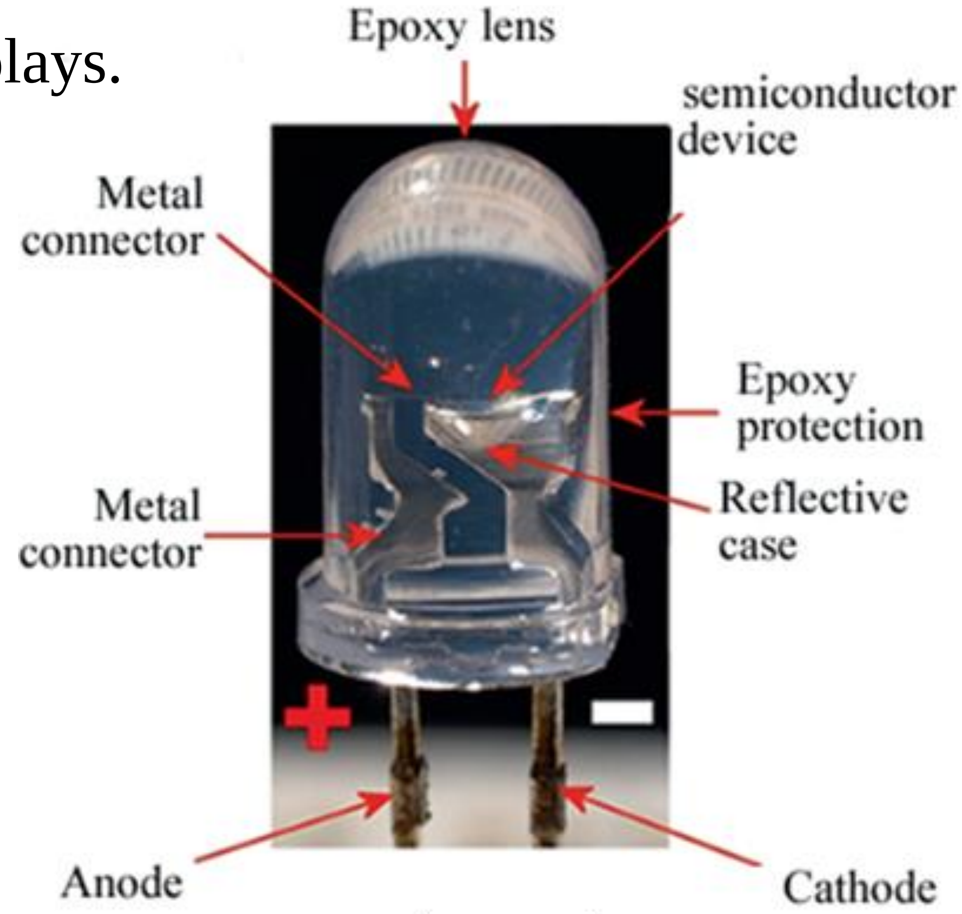
Key Properties of Semiconductors

- **Electroluminescence:** The ability to emit light when voltage is applied, forming the basis for **LEDs** and modern displays.





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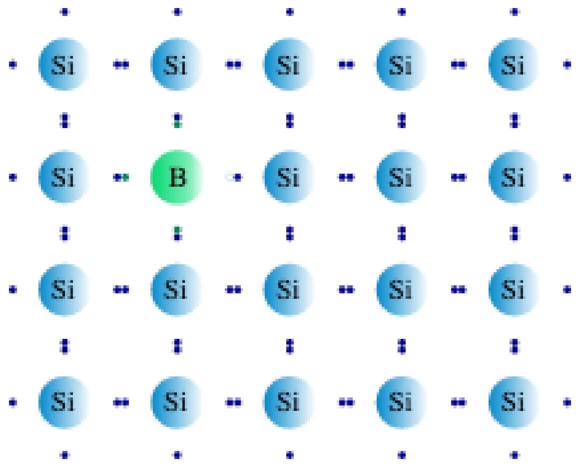
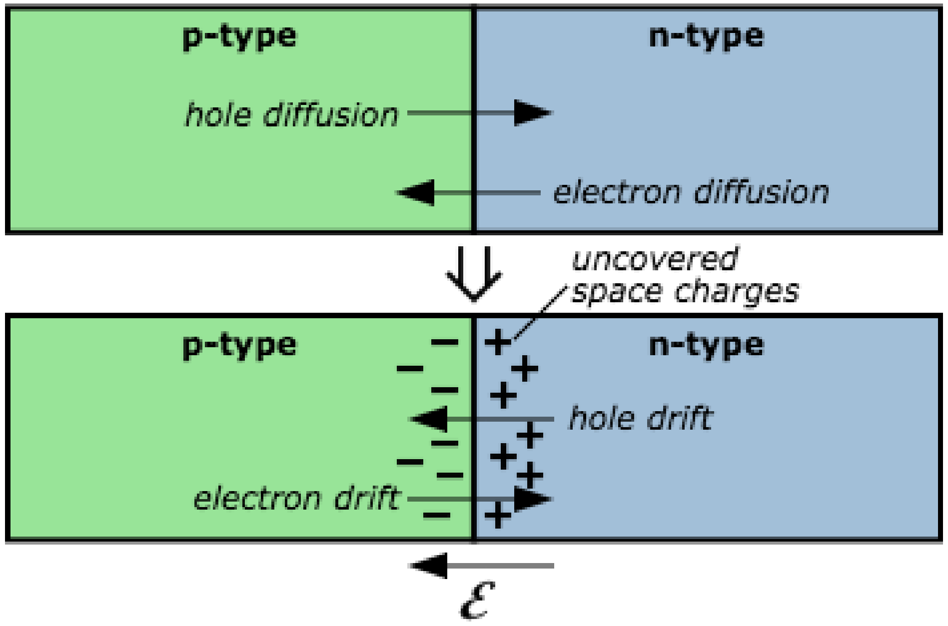
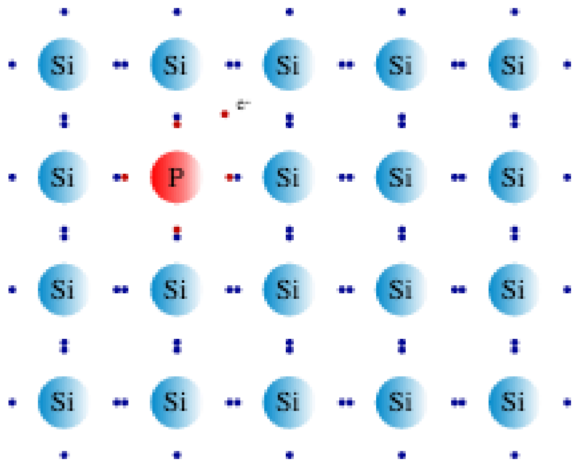
Key Properties of Semiconductors

- **Dopant Introduction:** Controlled "doping" alters electrical traits by creating excess electrons (N-type) or holes (P-type).







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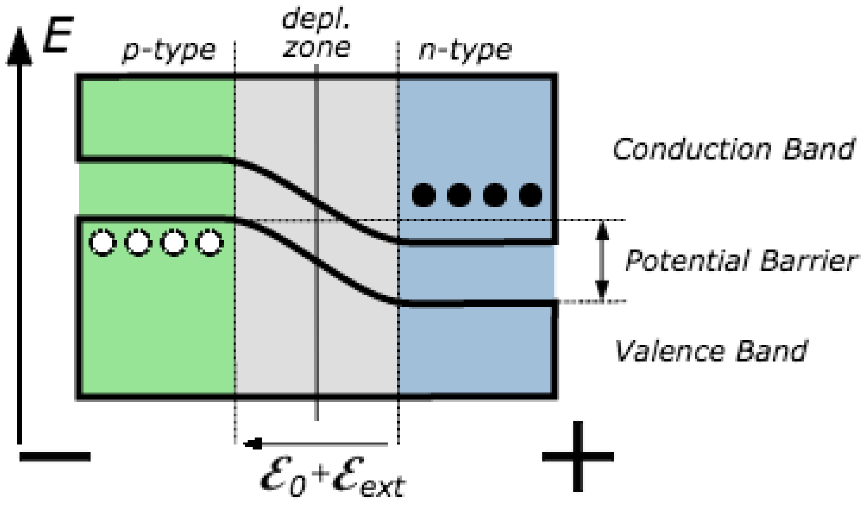
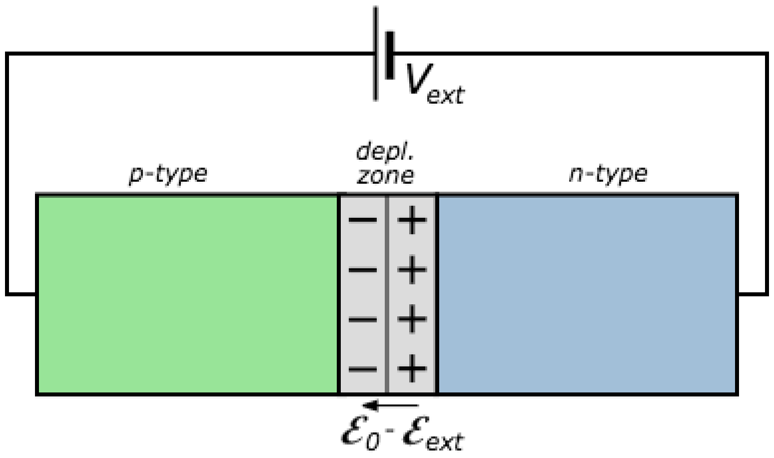
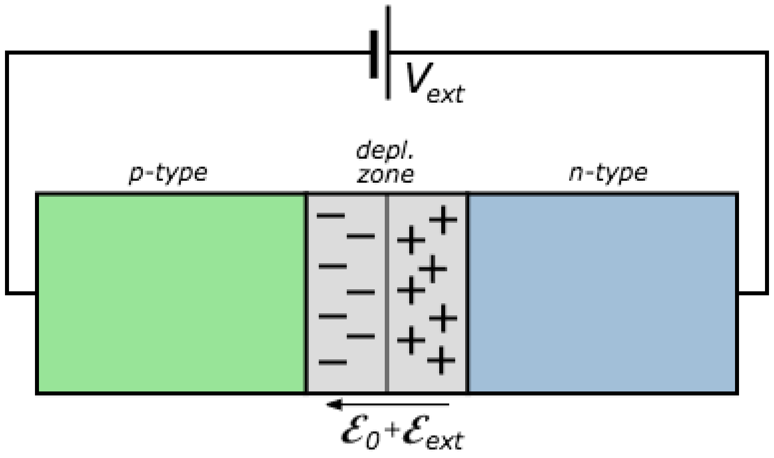
Key Properties of Semiconductors

- **Dopant Introduction:**





Forward Biased p-n Junction



Reverse Biased p-n Junction

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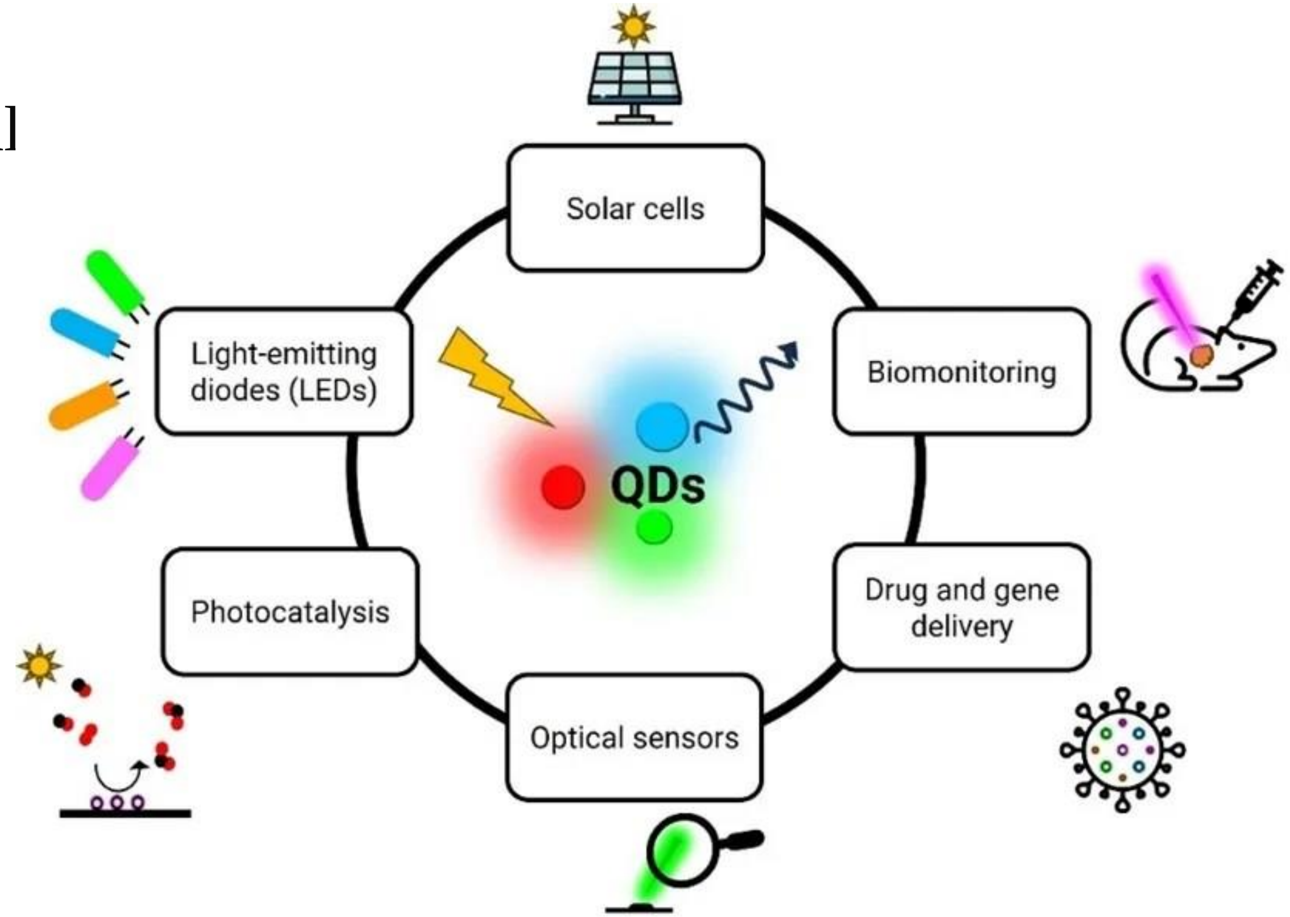
Key Properties of Semiconductors

- **Quantum Aspects:** At the nanoscal semiconductors reveal **quantum effects** used in quantum dots and advanced well structures.



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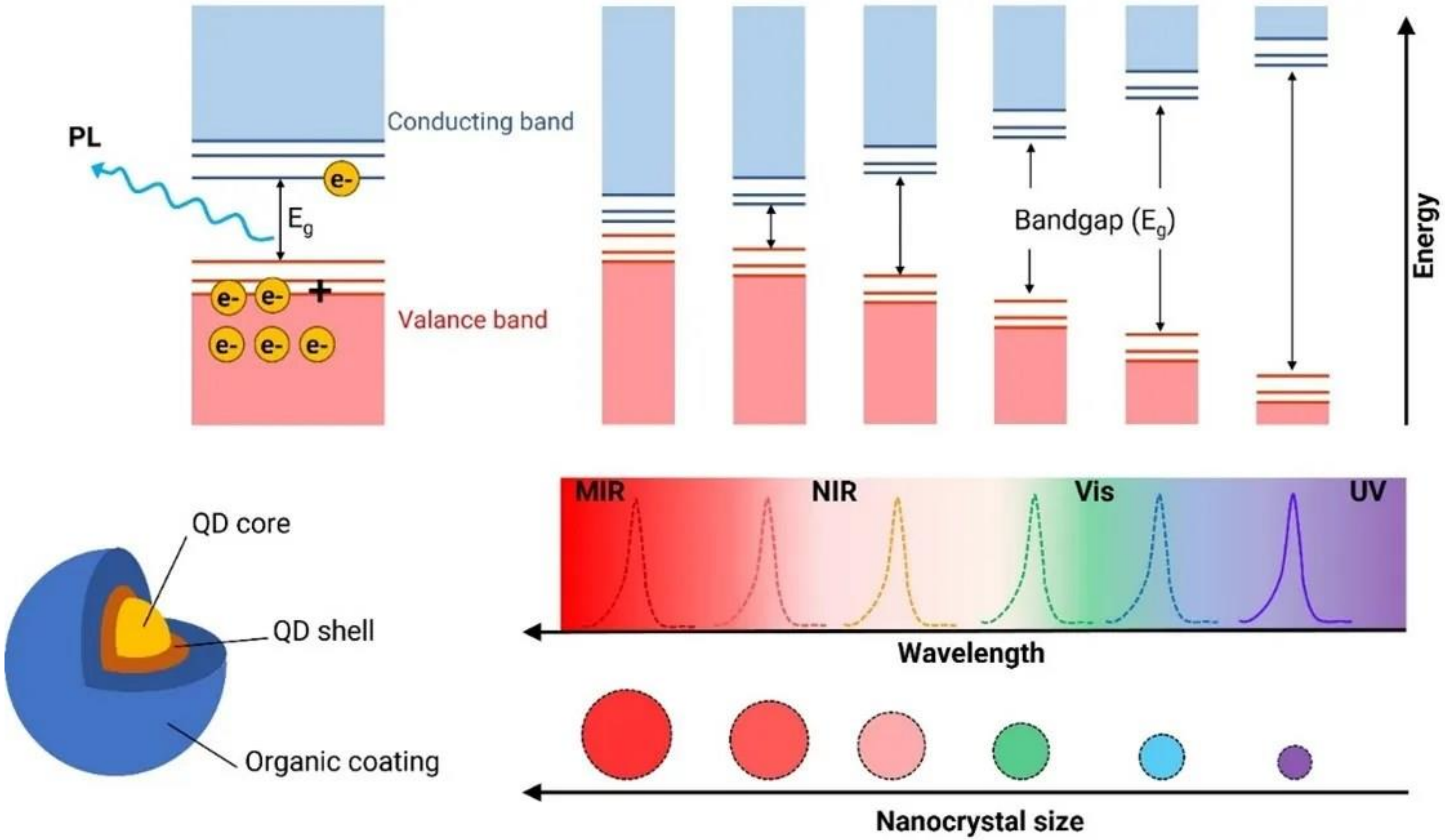
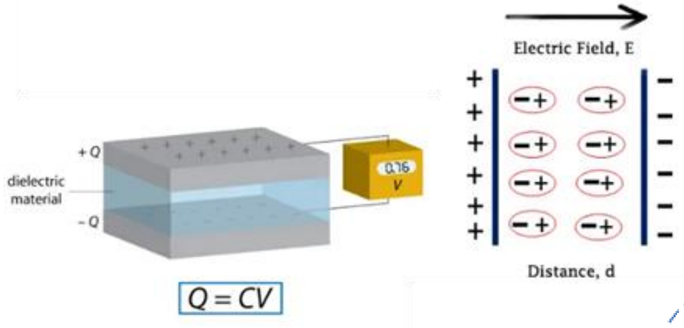
Key Properties of Semiconductors

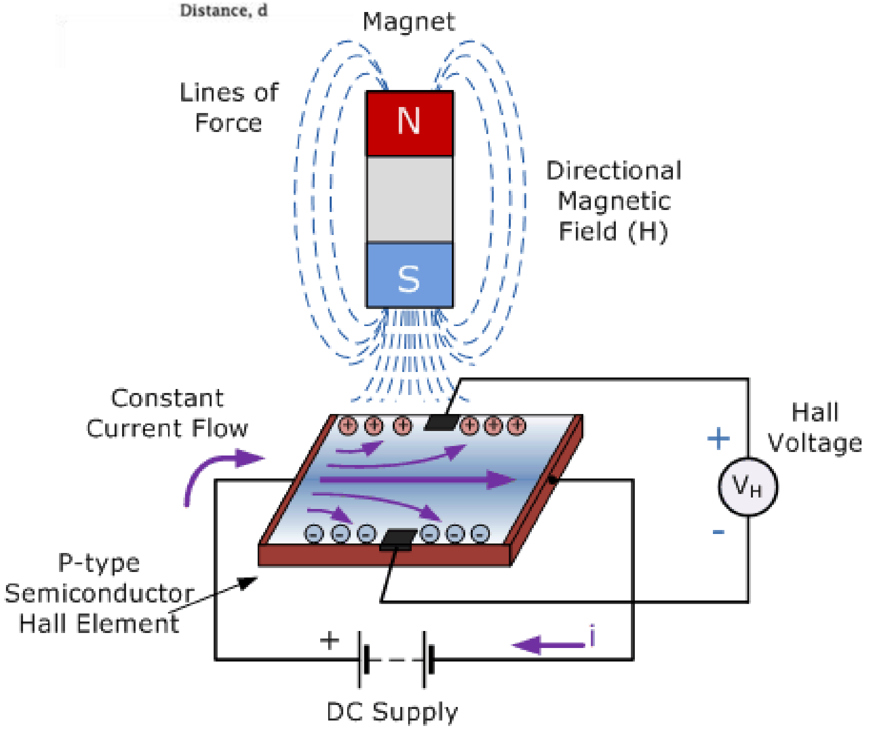
- **Quantum Aspects:** At the nanoscale, semiconductors reveal **quantum effects** used in quantum dots and advanced well structures.

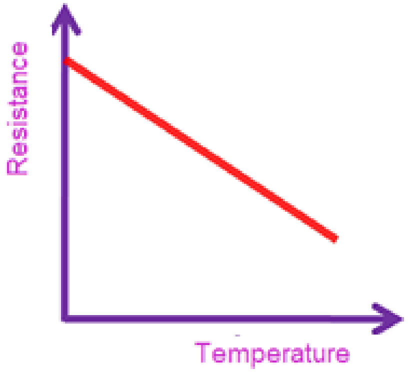


Key Properties of Semiconductors

- **Dielectric Qualities:** Can act as insulating dielectrics for use in capacitors and energy storage.
- **Hall Effect:** An electric field perpendicular to current generates a measurable voltage, used in **Hall sensors** for current measurement.
- **Heat Conductance:** Intermediate thermal conductivity allows for controlled heat dissipation in integrated circuits.







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Conductivity and Resistivity Dynamics

- **Temperature vs. Resistivity (ρ):**
  - **Unlike metals, semiconductor resistivity decreases** as temperature increases.
  - **Reason:** Higher temperatures provide more energy, allowing more electrons to jump from the Valence Band to the Conduction Band.
  - **This results in a negative temperature coefficient**.
- **Conductivity (σ):**
  - **At 0 Kelvin**, semiconductors act as perfect insulators.
  - **As temperature rises, they transition into conductors due to the mobilization of charge carriers.**

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Carrier Concentration and Mobility

- **Carrier Mobility:** Defines how quickly electrons and holes move through the material. Higher mobility equals faster, more efficient devices.
- **Carrier Concentration (n or p):** The number of charge carriers per unit volume.

$$n = Nc \cdot \exp\left(-\frac{Ec - Ef}{K.T}\right)$$

n: Carrier concentration

Nc : Effective density of state

Ec - Ef : Energy difference between conduction band and Fermi level

k: Boltzmann's constant

T: Temperature in Kelvin

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Classification of Semiconductors

Semiconductors are classified into two primary types based on their chemical purity:

- **Intrinsic Semiconductors:**
  - Chemically pure materials.
  - Charge carriers are created solely by thermal excitation.

Extrinsic Semiconductors:

- Materials where impurities (dopants) have been intentionally added.
- Further divided into **N-type** (electron-rich) and **P-type** (hole-rich).

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Thermal Behavior & Conductivity

- **At 0K (Absolute Zero):** All valence electrons are locked in covalent bonds. The material behaves as a **perfect insulator**.
- **Above 0K:** Thermal energy breaks covalent bonds, promoting electrons to the conduction band. This creates a "hole" in the valence band.
- **Charge Carriers:** The number of free electrons (n_e) is exactly equal to the number of holes (n_h).
- **Total Current:** $I = I_e + I_h$

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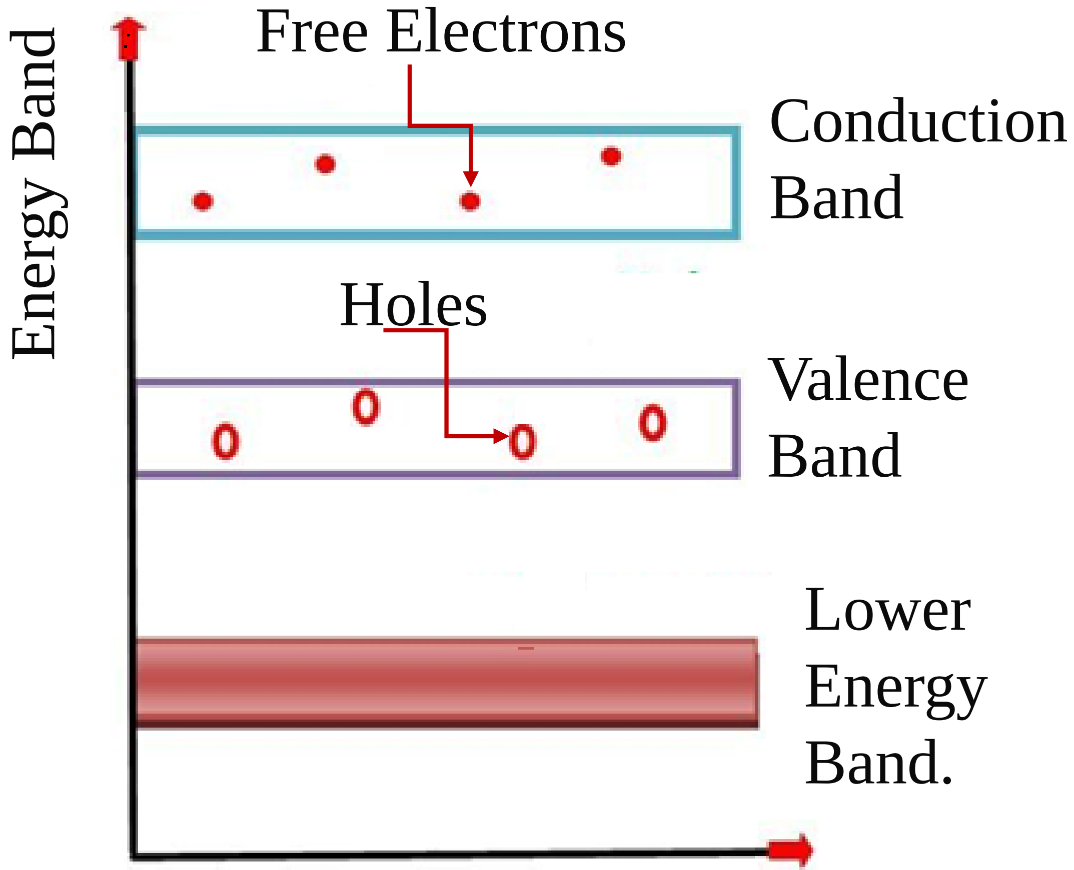
Energy Band Diagram: Intrinsic Semiconductors



Energy Band Diagram: Intrinsic Semiconductors

- **Carrier Generation & Band Structure**

In intrinsic semiconductors, the distribution of charge carriers is determined by the **Energy Band Gap (E_g)** and **Temperature (T)**. At finite temperatures, thermal excitation moves electrons from the Valence Band to the Conduction Band.

The Intrinsic Carrier Equation

The density of electrons in the conduction band (n) is calculated by the exponential relationship:

$$n = n_0 e^{-\frac{E_g}{2K_B T}}$$

E_g: Energy Band Gap (the energy required for excitation)

$K_B = 1.38 \times 10^{-23}\, J/K$: Boltzmann's Constant

T **:** Absolute Temperature in Kelvin

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Energy Band Diagram: Intrinsic Semiconductors

➢ **Key Insights**

- **Exponential Dependency:** The probability of finding an electron in the conduction band decreases exponentially as the band gap (Eg) **increases.**
- **Thermal Sensitivity:** Conductivity increases significantly with temperature as more covalent bonds break, providing more mobile charge carriers.
- **Equilibrium:** In a pure state, the number of electrons in the conduction band always equals the number of holes in the valence band.

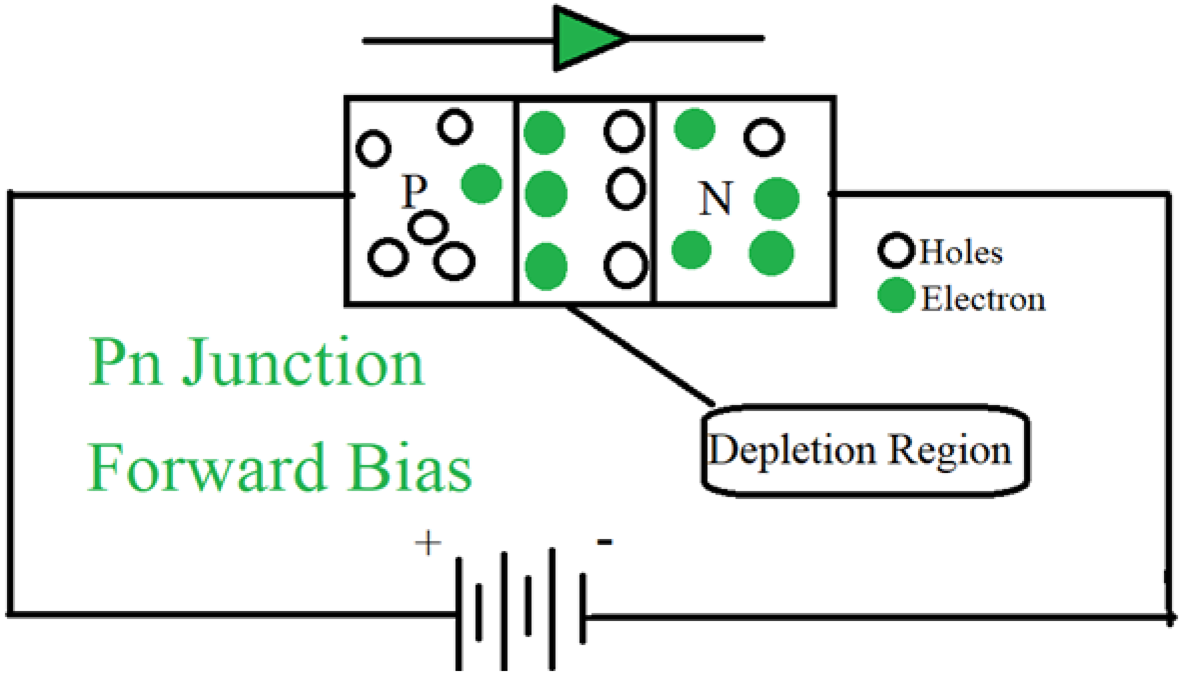
Extrinsic Semiconductors

- **N-type Semiconductors**
  - **Doping:** Doped with Group V pentavalent impurities (e.g., Phosphorus, Arsenic), which introduce excess electrons.
  - **Majority Carriers:** Electrons ($ne \gg nh$).
  - **Minority Carriers:** Holes.
  - **Conductivity:** Primarily due to electron movement ($I \approx Ie$).

- **P-type Semiconductors**
  - **Doping:** Doped with Group III trivalent impurities (e.g., Boron, Aluminum), which create "holes" (electron deficiencies).
  - **Majority Carriers:** Holes ($nh \gg ne$).
  - **Minority Carriers:** Electrons.
  - **Conductivity:** Primarily due to hole movement ($I \approx Ih$).

Formation and Biasing of a P-N Junction

- **Formation (Zero Bias)**
- **Materials: Carrier Movement:**
- **Depletion Region:**



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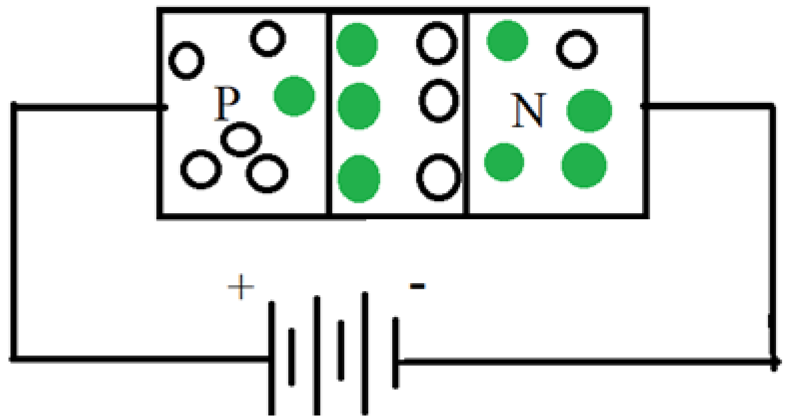
➢ Forward Bias (Active Current Flow)

- **Connection:** Positive voltage (+) applied to the **P-side**; negative voltage (-) applied to the **N-side**.



- **Effect:** The applied voltage opposes the built-in potential barrier, narrowing the depletion region.
- **Outcome:** The barrier is significantly reduced, allowing majority carriers to flow across the junction easily, resulting in a large current flow.

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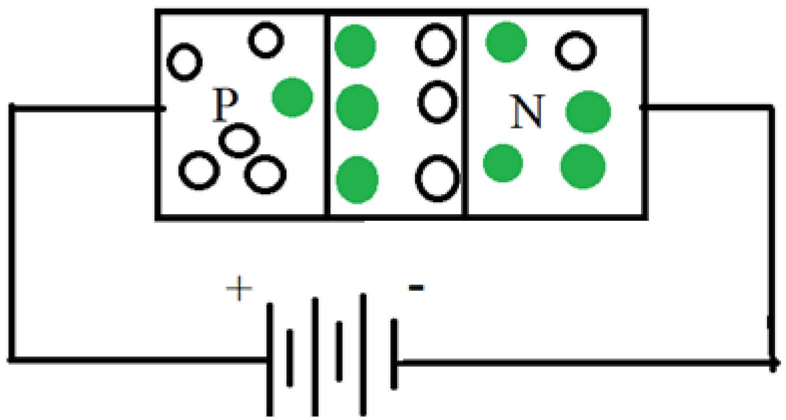
➢ Reverse Bias (Blocks Current Flow)

- **Connection:** Negative voltage (-) applied to the **P-side**; positive voltage (+) applied to the **N-side**.



- **Effect:** The applied voltage reinforces the built-in potential barrier, widening the depletion region.
- **Outcome:** The barrier increases, preventing the flow of majority carriers and blocking significant current flow (except for a very small leakage current).

Intrinsic vs. Extrinsic Semiconductors

Feature	Intrinsic Semiconductor	Extrinsic Semiconductor
Purity	Pure material (e.g., Si, Ge)	Doped with impurities (Group III or V)
Charge Carriers	Generated by thermal energy (equal electrons & holes)	Doping creates excess electrons (N-type) or holes (P-type).
Conductivity	Very low at room temperature	Significantly higher (controllable)
Energy Gap	Relatively large, fixed band gap	Marginally altered by dopants
Usage	Limited direct use; foundational for understanding.	Used widely in electronic devices (transistors, solar cells).

Applications, Importance, Advantages, and Disadvantages of Semiconductors

- **Common Applications**

Semiconductors are crucial to modern life, forming the core of countless devices:

- **Computers/Laptops:** CPUs, GPUs, and microprocessors process all data.
- **Basic Electronics:** Switches, diodes, transistors, and integrated circuits (ICs).
- **Lighting:** Light-Emitting Diodes (LEDs) for efficient home, vehicle, and display lighting.
- **Communication:** Routers, modems, satellites, and GPS systems rely on semiconductor chips.
- **Smart Technology:** Wearable tech (smartwatches, rings) and home automation (thermostats, security cameras).

➢ Importance & Advantages

- **Miniaturization:** Allows for compact, portable devices (microscopic scale manufacturing).
- **Energy Efficiency:** Consume low power during operation.
- **Durability:** Solid-state with no moving parts; shock-resistant and long lifespan.
- **High Speed:** Extremely high switching speeds enable fast digital operations.
- **Light Emission:** Certain materials emit light when current passes (LEDs, laser diodes).

Disadvantages & Limitations

- **Temperature Vulnerability:** Performance and reliability can shift significantly with temperature changes.
- **High Production Costs:** Manufacturing requires complex processes and specialized facilities.
- **Purity Reliance:** Minor impurities drastically change electrical characteristics.
- **Degradation:** Performance inconsistency and potential wear out over extended use.

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End chapter 1

[Video 1](https://www.youtube.com/watch?v=60Qz051rD_w&t=717s)
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[Video 2](https://www.infineon.com/our-stories/how-a-chip-is-made)
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