**🔬 Why Graphite is a Good Conductor of Electricity**

1. **Atomic Structure of Graphite**
   * Graphite is made of **carbon atoms** arranged in **flat layers** (called graphene sheets).
   * Each carbon atom is bonded to **only 3 other carbon atoms** in a hexagonal pattern.
2. **Delocalized Electron**
   * Carbon has **4 valence electrons**. In graphite:
     + **3 electrons** form strong covalent bonds with neighboring atoms.
     + The **4th electron is free** — it does **not** bond.
   * This **free electron is delocalized**, meaning it can **move freely across the layer**.
3. **Electron Mobility = Conductivity**
   * These **mobile electrons** act like a "sea of charge" — similar to metals.
   * They can carry electric current when a voltage is applied.
4. **Layer Structure Helps**
   * The layers are held together by **weak forces** (van der Waals), so electrons can move **easily within layers** but **not between them**.
   * That's why graphite conducts **in the plane of the layers**, but not vertically.

**Why do electrons have a negative charge?**

Electrons are assigned a negative charge by convention, primarily because Benjamin Franklin's early experiments led to the assumption that the charge acquired by a glass rod rubbed with silk was "positive," and the opposite charge was then termed "negative".

Here's a more detailed explanation:

* **Historical Context:**

Benjamin Franklin, in his experiments with electricity, established the concept of positive and negative charges.

  **Franklin's Choice:**

He arbitrarily designated the charge acquired by a glass rod rubbed with silk as "positive," and the opposite charge as "negative".

  **Electron Discovery:**

Later, when electrons were discovered, they were found to be the carriers of the "negative" charge, and the positively charged particles were called protons.

  **Convention:**

This initial designation by Franklin, although arbitrary, has become the standard convention in physics and chemistry.

  **Opposite Charges:**

It is important to note that the charge of a proton and an electron are opposite, so that a neutral atom has the same number of protons and electrons, resulting in zero net charge

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Total energy of the electron: Slide 32:

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Newton's second law of motion:

At any instant of time, the net force on a body is equal to the body's acceleration multiplied by its mass or, equivalently, the rate at which the body's momentum is changing with time.

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**energy levels are quantized**, meaning that a system can only exist at specific, discrete energy values, rather than a continuous range of values

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**🧠 Explanation of Each Row**

**1. Quantized orbits (n=1,2,…)(n = 1, 2, \ldots)(n=1,2,…) → Continuous energy bands**

* **Bohr Atom**:  
  In the hydrogen atom, electrons can only occupy discrete orbits (or energy levels), labeled by an integer quantum number nnn. Each level corresponds to a specific energy WnW\_nWn​.
* **Solid Material**:  
  In a solid, atoms are packed closely together. Their overlapping orbitals cause these discrete levels to **broaden into continuous energy bands**, because electrons can occupy a range of closely spaced energy states.

**2. Negative Wn​ = bound → Valence band (bound states)**

* **Bohr Atom**:  
  The negative energy Wn<0 indicates that the electron is **bound to the nucleus**. The more negative it is, the more tightly the electron is held.
* **Solid Material**:  
  Electrons in the **valence band** are also in bound states — they are still associated with specific atoms and cannot move freely through the material without additional energy.

**3. Ionization limit W=0 → Bottom of conduction band**

* **Bohr Atom**:  
  When W=0W, the electron is **no longer bound** to the atom — it has enough energy to escape (i.e., it’s ionized).
* **Solid Material**:  
  The **bottom of the conduction band** is the lowest energy an electron can have while being "free" to move through the material. It's like the “ionized” state in an atom, but in a crystal lattice.

**🧩 Why this table matters:**

It shows that:

* Atomic **discrete energy levels** evolve into **energy bands** in solids.
* The **bound vs. free** nature of electrons in atoms carries over to the **valence vs. conduction band** picture.
* Bohr’s quantum model forms a foundation for understanding **electrical behavior in materials** — especially in **semiconductors** and **insulators**.

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This slide explains how **energy bands form in solids** and the role of the **quantum number nnn** in transitioning from discrete atomic levels (Bohr model) to continuous bands in solid-state materials. Here's a breakdown of the key points:

**🔹 Valence Band**

* Formed from the **outermost electron levels** of atoms (e.g., quantum levels where n=2,3n = 2, 3n=2,3).
* These electrons are **bound** and not free to move easily.
* In solids, these orbitals **overlap**, and the discrete energy levels merge into a **band**.

**🔹 Conduction Band**

* Formed from **higher energy states** that are unoccupied in a neutral atom.
* Electrons in this band are **free or nearly free**, contributing to **electrical conduction**.

**🔹 Band Gap (EgE\_gEg​)**

* The **energy difference** between the conduction band and valence band.
* A **key factor** in determining whether a material is a conductor, semiconductor, or insulator:
  + **Small EgE\_gEg​** → semiconductor
  + **Large EgE\_gEg​** → insulator
  + **No EgE\_gEg​** (overlap) → conductor

**🔹 Energy Bands & Role of Quantum Number nnn**

* In the **Bohr model**, nnn defines **discrete energy levels** (orbits).
* In **solids**, due to atomic proximity, orbitals **overlap**, and these discrete levels **form bands**.
* These **energy bands** are separated by **band gaps**, and this structure governs **electrical behavior**.

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**Acceptor and donor:**

If a small percentage of trivalent or pentavalent atoms are added to intrinsic silicon or germanium, a *doped, impure,* or *extrinsic* semiconductor is formed.

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Lecture II: 16-04-2025

Mass action law: Derivation:

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Analogy to understand: NC​ as the number of **available hotel rooms** (states) in the conduction band. Electrons (guests) can move in if energy (money) allows — but the rooms must exist first!

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**Charge neutrality equation**

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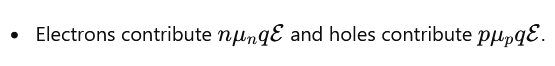
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Slide 53: Conductivity and career mobility:   
?????? Why

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Relevance of this equation:

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| **Symbol** | **Meaning** |
| --- | --- |
| nin\_ini​ | Intrinsic carrier concentration (number of free electrons or holes in an undoped semiconductor) |
| A0 | A material-dependent constant that includes the **effective density of states** in conduction and valence bands |
| T | Absolute temperature (in Kelvin) |
| T3 | Shows that the number of available energy states increases with TTT |
| EG0 | Bandgap energy at 0 K (energy needed to excite an electron across the gap) |
| K | Boltzmann constant ≈1.38×10−23 J/K\approx 1.38 \times 10^{-23} \, \text{J/K}≈1.38×10−23J/K |
|  | Exponential part that shows how hard it is to excite electrons across the bandgap (falls with larger bandgap or lower temperature) |

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Hall effect:

Case I:

No magnetic field:  
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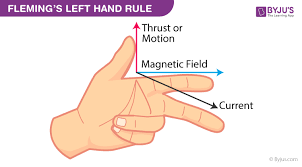
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Magnetic field is applied:

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The magnetic field is into the metal and then impact the flow of direction of electroncs.



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So now the electrons and holes are forming like a plate.

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Fe is electric filed and Fm is magnetic field.

This above will form plates in equilibrium. The difference in potential between the two plates is the hall voltage.

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This is how we calculate the hall voltage.

**Relevance of hall coefficient:**

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**Summary table in reverse bias of p-n junction:**

| **Carrier Type** | **Region** | **Action in Reverse Bias** | **Contributes to Current?** |
| --- | --- | --- | --- |
| **Majority (holes)** | p-type | Repelled from junction | ❌ No (blocked by field) |
| **Majority (electrons)** | n-type | Repelled from junction | ❌ No |
| **Minority (electrons)** | p-type | Drifted across junction by field | ✅ Yes (small drift current) |
| **Minority (holes)** | n-type | Drifted across junction by field | ✅ Yes (small drift current) |

**Summary table in forward bias of p-n junction:**

**💡 Is There Diffusion? Yes!**

**🔄 Carrier Injection & Diffusion:**

* The injected **minority carriers** (electrons in p, holes in n) **diffuse** away from the junction.
* This **diffusion** is the **main component of current** in forward bias.
* This exponential behavior arises because of **diffusion current** from carrier injection.

**🌪 Is There Drift? Only Inside Depletion Region**

* **Drift current** is present **inside the depletion region**:
  + The built-in field **sweeps out** the minority carriers that arrive at the edge.
* But in the **neutral regions**, carrier transport is dominated by **diffusion**.

| **Carrier Type** | **Region** | **Mechanism** | **Contribution** |
| --- | --- | --- | --- |
| **Majority (holes)** | p-type → n | Cross junction (injected) | ✅ Major part of current |
| **Majority (electrons)** | n-type → p | Cross junction (injected) | ✅ Major part of current |
| **Minority (electrons)** | p-type | Drift (quick removal) | ✅ Sustains current |
| **Minority (holes)** | n-type | Drift (quick removal) | ✅ Sustains current |

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| **Symbol** | **Meaning** |
| --- | --- |
| Ipn(0)I\_{pn}(0)Ipn​(0) | **Hole diffusion current** injected from **p to n region** at x=0x = 0x=0 |
| A | **Cross-sectional area** of the diode |
| Q | **Elementary charge** of an electron ≈ 1.6×10−19 C1.6 \times 10^{-19} \, \text{C}1.6×10−19C |
| Dp​ | **Diffusion coefficient of holes** (in the n-region) – quantifies how fast holes spread |
| Lp​ | **Diffusion length of holes** in the n-region = Dpτp\sqrt{D\_p \tau\_p}Dp​τp​​, where τp\tau\_pτp​ is hole lifetime |
| pn(0) | **Hole concentration at edge of depletion region in n-region under bias** |
| pn0​ | **Equilibrium hole concentration** in the n-region (no bias) |

When you bring two materials into contact (e.g., a **p-type** and **n-type** semiconductor in a p–n junction), the **Fermi levels** (which represent the chemical potential for electrons) are not aligned. To reach equilibrium, **charge flows** across the junction. This charge transfer leads to:

* Formation of a **depletion region** with **immobile ions**.
* An **electric field** is set up across the junction.
* The conduction and valence bands bend—this is **band bending**.

**🔷 Why is Band Bending Important?**

1. **Creates a Potential Barrier**:
   * The bending of bands forms a **barrier potential** (e.g., built-in potential V0​ in a p–n junction).
   * This barrier **blocks carrier flow** (electrons or holes) under **zero or reverse bias**, thus enabling **blocking behavior**.
2. **Enables Controlled Switching**:
   * When a forward bias is applied:
     + The band bending is reduced.
     + Carriers (electrons from n, holes from p) can now **overcome the barrier**, resulting in **conduction**.
   * This transition from blocking to conduction forms the basis of **switching behavior** in power devices.
3. **Barrier Height Determines Device Ratings**:
   * Higher barrier = better blocking capability.
   * Proper doping and junction engineering are used to control the extent of band bending and hence the **breakdown voltage**.

**🔷 Visual Summary**

* **Reverse Bias** → Increased band bending → High potential barrier → **No current** (blocking).
* **Forward Bias** → Flattened bands → Reduced barrier → **Current flows** (conduction).

**🔷 Real-World Relevance**

* In **diodes**, band bending allows the device to block voltage when off and conduct when forward-biased.
* In **MOSFETs**, bending in the channel controls the formation of the conduction path.
* In **IGBTs**, it controls injection and recombination during switching.

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**Tunneling** in semiconductors is a quantum mechanical phenomenon where electrons can pass through a potential barrier, even if they don't have enough energy to overcome it classically. This happens because of the wave-like nature of electrons, where their wavefunction (probability of finding the electron) has a non-zero probability of existing on both sides of the barrier.

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| **Switch Type** | **Voltage Direction** | **Current Direction** | **Quadrants** | **Examples** |
| --- | --- | --- | --- | --- |
| Single-Quadrant | Unidirectional | Unidirectional | I | Diode, basic IGBT or MOSFET |
| Two-Quadrant (Voltage-Bidirectional) | Bidirectional | Unidirectional | I and III | Back-to-back IGBTs |
| Two-Quadrant (Current-Bidirectional) | Unidirectional | Bidirectional | I and II | MOSFET with body diode |
| Four-Quadrant | Bidirectional | Bidirectional | I, II, III, IV | H-Bridge with 4 IGBTs or MOSFETs |

Relevance of adding n- layer in power diode?

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| **Function** | **Role of n⁻ Layer** |
| --- | --- |
| Reverse Voltage Blocking | Extends depletion region, increases VBDV\_{\text{BD}} |
| Electric Field Management | Avoids premature breakdown, distributes field |
| Avalanche Protection | Allows soft breakdown under overvoltage |
| Forward Conduction Impact | Increases RonR\_{on} and forward drop |

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