**Physics for Information Science - PH3256**

**PART-C**

**Unit-I Electrical Properties of Materials**

**1. Classical Free Electron Theory**

**Basic Assumptions of Classical Free Electron Theory:**

The classical free electron theory was proposed by Drude and later modified by Lorentz. The key assumptions are:

1. **Free Electron Approximation**: Metals contain a large number of free electrons which move randomly like gas molecules in a container.
2. **Electrons Obey Classical Laws**: Electrons obey classical mechanics and follow Maxwell-Boltzmann statistics.
3. **Neglect of Electron-Electron and Electron-Ion Interactions**: The mutual interactions between electrons and the interaction with ion cores are neglected.
4. **Scattering**: Electrons undergo collisions with fixed ion cores, which is responsible for resistance in the material.
5. **Constant Relaxation Time (τ)**: The average time between two successive collisions is constant.

**Electrical Conductivity (σ):**

Let:

* nn = number of free electrons per unit volume
* ee = charge of electron
* mm = mass of electron
* ττ = relaxation time
* EE = applied electric field

The force on an electron:

F=−eEF = -eE

Acceleration of electron:

a=Fm=−eEma = \frac{F}{m} = -\frac{eE}{m}

Drift velocity:

vd=a⋅τ=−eEτmv\_d = a \cdot τ = -\frac{eEτ}{m}

Current density:

J=nevd=ne(−eEτm)=ne2τmEJ = n e v\_d = n e \left( -\frac{eEτ}{m} \right) = \frac{n e^2 τ}{m} E

Comparing with Ohm's law J=σEJ = σE, we get:

σ=ne2τmσ = \frac{n e^2 τ}{m}

**Thermal Conductivity (K):**

Using kinetic theory, thermal conductivity:

K=13nvλCvK = \frac{1}{3} n v \lambda C\_v

Where:

* vv = average velocity
* λ\lambda = mean free path
* CvC\_v = specific heat per electron =32k= \frac{3}{2}k
* kk = Boltzmann constant

So,

K=13nvλ⋅32k=12nvλkK = \frac{1}{3} n v \lambda \cdot \frac{3}{2}k = \frac{1}{2} n v \lambda k

**Wiedemann-Franz Law:**

Relating thermal and electrical conductivity:

Kσ=12⋅vλk(ne2τ/m)=LT(Lorenz number)\frac{K}{σ} = \frac{1}{2} \cdot \frac{v \lambda k}{(n e^2 τ / m)} = L T \quad \text{(Lorenz number)} ⇒KσT=constant\Rightarrow \frac{K}{σ T} = \text{constant}

**Successes of the Theory:**

* Explains Ohm’s law.
* Derives a basic relation between conductivity and physical parameters.
* Explains Wiedemann-Franz law.

**Failures of the Theory:**

* Could not explain:
  + Temperature dependence of conductivity.
  + Heat capacity of metals being much lower than predicted.
  + Paramagnetic and diamagnetic properties.
  + Differences in conduction of different metals.
* Does not consider quantum effects (e.g., Pauli Exclusion Principle).
* Assumes electrons follow Maxwell-Boltzmann statistics instead of Fermi-Dirac.

**2. Schrödinger Equation in a 3D Box**

**Assumptions:**

* A particle of mass mm is confined in a cubical box of side LL.
* Infinite potential outside the box V=∞V = \infty, and zero potential inside the box V=0V = 0.
* Boundaries: x,y,z∈[0,L]x, y, z \in [0, L]

**Time-Independent Schrödinger Equation (3D):**

−ℏ22m∇2ψ(x,y,z)=Eψ(x,y,z)- \frac{\hbar^2}{2m} \nabla^2 \psi(x, y, z) = E \psi(x, y, z)

Since potential inside is 0:

∇2ψ+2mEℏ2ψ=0\nabla^2 \psi + \frac{2mE}{\hbar^2} \psi = 0

Assume separable solution:

ψ(x,y,z)=X(x)Y(y)Z(z)\psi(x, y, z) = X(x)Y(y)Z(z)

Substituting into the equation:

1Xd2Xdx2+1Yd2Ydy2+1Zd2Zdz2=−2mEℏ2\frac{1}{X} \frac{d^2X}{dx^2} + \frac{1}{Y} \frac{d^2Y}{dy^2} + \frac{1}{Z} \frac{d^2Z}{dz^2} = -\frac{2mE}{\hbar^2}

Each term equals a constant:

d2Xdx2+kx2X=0,d2Ydy2+ky2Y=0,d2Zdz2+kz2Z=0\frac{d^2X}{dx^2} + k\_x^2 X = 0,\quad \frac{d^2Y}{dy^2} + k\_y^2 Y = 0,\quad \frac{d^2Z}{dz^2} + k\_z^2 Z = 0

With boundary conditions X(0)=X(L)=0X(0) = X(L) = 0, solution:

X(x)=2Lsin⁡(nxπxL),nx=1,2,3,...X(x) = \sqrt{\frac{2}{L}} \sin \left( \frac{n\_x \pi x}{L} \right), \quad n\_x = 1, 2, 3, ...

Similarly for Y and Z.

**Eigenfunctions:**

ψnx,ny,nz(x,y,z)=(2L)3/2sin⁡(nxπxL)sin⁡(nyπyL)sin⁡(nzπzL)\psi\_{n\_x,n\_y,n\_z}(x, y, z) = \left( \frac{2}{L} \right)^{3/2} \sin \left( \frac{n\_x \pi x}{L} \right) \sin \left( \frac{n\_y \pi y}{L} \right) \sin \left( \frac{n\_z \pi z}{L} \right)

**Eigenvalues:**

Total energy:

Enx,ny,nz=ℏ2π22mL2(nx2+ny2+nz2)E\_{n\_x,n\_y,n\_z} = \frac{\hbar^2 \pi^2}{2m L^2} (n\_x^2 + n\_y^2 + n\_z^2)

**Key Points:**

* Each quantum number nx,ny,nzn\_x, n\_y, n\_z must be a positive integer.
* Energy levels are quantized.
* Degeneracy occurs when different combinations of quantum numbers give the same energy.

**Unit II Semiconductor Physics**

**1. What is Hall Effect? Derive an expression for Hall coefficient. Describe an experimental setup for the measurement of the hall coefficient and mention its applications**.

**Hall Effect**

**Definition:**

**Hall Effect** is the development of a transverse voltage (Hall Voltage) across a conductor or semiconductor carrying current when placed in a perpendicular magnetic field.

**Explanation:**

When a current-carrying conductor is placed in a magnetic field perpendicular to the direction of current, a **Lorentz force** acts on the charge carriers, deflecting them to one side of the material. This causes a potential difference across the opposite faces — known as the **Hall Voltage (V\_H)**.

**Diagram:**

B (into the page)

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| | ← Accumulation of electrons (negative side)

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I (Current from left to right)

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* **B**: Magnetic field perpendicular to the plane
* **I**: Current through the conductor
* **V\_H**: Appears perpendicular to both I and B

**Derivation of Hall Coefficient:**

Let:

* II = current
* BB = magnetic field
* qq = charge of the carrier
* nn = number of charge carriers per unit volume
* VHV\_H = Hall voltage
* tt = thickness of the sample

**Hall electric field (E\_H):**

When force due to electric field balances magnetic force:

qEH=qvdB⇒EH=vdBq E\_H = q v\_d B \Rightarrow E\_H = v\_d B

Where vd=InqAv\_d = \frac{I}{n q A}, and A=w⋅tA = w \cdot t

So,

EH=IBnqAE\_H = \frac{I B}{n q A}

Since VH=EH⋅wV\_H = E\_H \cdot w, we get:

VH=IBnqtV\_H = \frac{I B}{n q t}

**Hall Coefficient (R\_H):**

RH=EHJB=1nqR\_H = \frac{E\_H}{J B} = \frac{1}{n q}

Where:

* JJ is current density =IA= \frac{I}{A}

Thus,

RH=VH⋅tI⋅BR\_H = \frac{V\_H \cdot t}{I \cdot B}

**Experimental Setup:**

* A rectangular semiconductor sample.
* Current applied along the length.
* Magnetic field applied perpendicular to the sample.
* Hall voltage measured across the width using a voltmeter.

**Applications of Hall Effect:**

1. **Determining carrier type**: Positive (holes) or negative (electrons).
2. **Measuring carrier concentration** in semiconductors.
3. **Magnetic field sensing** – used in Hall sensors.
4. **Current sensing** in electronic circuits.
5. **Non-contact position sensing** (automotive, robotics).

**2.** **Describe the construction and working of Schottky Diode and Ohmic contact with neat diagrams.**

**Schottky Diode**

**Construction:**

* Made by contacting a **metal** (e.g., platinum, gold) with **N-type semiconductor**.
* Forms a **metal-semiconductor junction**, not P-N junction.
* Very thin depletion region due to majority carrier movement.

**Diagram:**

Metal Semiconductor

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|─────| N |───

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Schottky barrier

**Working:**

* **Forward Bias**: Electrons from semiconductor flow easily to the metal — **low forward voltage (~0.3V)**.
* **Reverse Bias**: Very little current flows — no significant reverse conduction.

**Advantages:**

* Fast switching speed.
* Low forward voltage drop.
* Ideal for high-frequency applications.

**Ohmic Contact**

**Definition:**

An **Ohmic contact** is a metal-semiconductor junction that allows current to pass in **both directions** without any barrier — **linear I-V characteristics**.

**Construction:**

* Achieved by **heavy doping** of the semiconductor at the junction.
* Commonly used metals: aluminum, gold, or nickel.

**Diagram:**

Metal Heavily Doped Semiconductor

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|─────| N++ or P++ region |───

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Ohmic contact

**Working:**

* Contact allows electrons/holes to flow freely.
* No rectification — behaves like a resistor.

**Applications:**

**Schottky Diode:**

* Power rectifiers
* RF mixers and detectors
* High-speed switching circuits

**Ohmic Contact:**

* Used in connecting leads to semiconductor devices (transistors, diodes, ICs)
* Contact pads in IC fabrication

**Unit III Magnetic properties of materials**

**9. (i) Explain about the origin of ferromagnetism and exchange interaction in ferromagnetic materials.**

**(ii) Discuss about saturation magnetisation and Curie temperature.**

**(iii) Explain M versus H behaviour**

**(iv).Write the difference between hard and soft magnetic materials with examples.**

**(i) Origin of Ferromagnetism and Exchange Interaction**

**Ferromagnetism:**

Ferromagnetism is a phenomenon where certain materials (like Fe, Co, Ni) exhibit **spontaneous magnetization** even in the absence of an external magnetic field.

**Origin:**

* Caused by **alignment of magnetic moments** (spins of electrons) in the same direction.
* Each atom behaves like a tiny magnet due to the **spin** and **orbital motion** of electrons.
* In ferromagnetic materials, magnetic moments in a region (called a **domain**) align parallel, leading to a strong net magnetization.

**Exchange Interaction:**

* The **exchange interaction** is a quantum mechanical effect due to the **Pauli Exclusion Principle**.
* Electrons with **parallel spins** have **lower energy** due to spatial separation, favoring alignment.
* The energy associated with exchange interaction is:

E=−2JS⃗i⋅S⃗jE = -2J \vec{S}\_i \cdot \vec{S}\_j

Where:

* + JJ = exchange integral (positive for ferromagnets)
  + S⃗i,S⃗j\vec{S}\_i, \vec{S}\_j = spins of neighboring atoms

If J>0J > 0, spins align parallel → **ferromagnetism**.  
If J<0J < 0, spins align antiparallel → **antiferromagnetism**.

**(ii) Saturation Magnetization and Curie Temperature**

**Saturation Magnetization (Ms):**

* It is the **maximum magnetization** that a ferromagnetic material can achieve under an external magnetic field.
* At this point, **all magnetic domains** are aligned.
* Beyond this, increasing the magnetic field **does not increase** magnetization.

**Curie Temperature (Tc):**

* The **temperature above which a ferromagnetic material loses its magnetic properties** and becomes paramagnetic.
* At T>TcT > T\_c, thermal energy overcomes exchange interaction.
* Example: For iron, Tc≈770∘CT\_c ≈ 770^\circ C

**(iii) M vs H Behaviour (Magnetization Curve)**

The **M vs H** (Magnetization vs Magnetic Field) graph shows how a ferromagnetic material responds to an external magnetic field.

**Key Features:**

* **Initial Magnetization Curve**: Starts from origin; magnetization increases as H increases.
* **Saturation**: Point where M becomes constant.
* **Hysteresis Loop**: When H is varied cyclically, the material shows **magnetic memory**.

**Diagram Description:**

M (Magnetization)

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│ / ← Saturation

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* **Retentivity**: Magnetization left when H = 0.
* **Coercivity**: Field needed to reduce M to 0.

**(iv) Hard vs Soft Magnetic Materials**

| **Property** | **Hard Magnetic Materials** | **Soft Magnetic Materials** |
| --- | --- | --- |
| **Coercivity** | High | Low |
| **Retentivity** | High | Low |
| **Hysteresis Loss** | Large | Small |
| **Domain wall motion** | Difficult | Easy |
| **Uses** | Permanent magnets | Transformer cores, inductors |
| **Examples** | Alnico, Ferrites | Soft iron, Permalloy |

**Unit IV Optical properties ofmaterials**

**1. Explain the principle, construction and working of**

**(i). Semiconductor diode laser with necessary diagrams.**

**(ii). Photocurrent in P-N diode and solar cell**

**1. (i) Semiconductor Diode Laser**

**Principle:**

A **semiconductor diode laser** works on the principle of **electroluminescence** and **stimulated emission**. When electrons recombine with holes in a forward-biased p-n junction, **photons** are emitted. Under certain conditions, **coherent and monochromatic light** is produced (laser).

**Construction:**

* Made using **direct bandgap semiconductors** like GaAs.
* Contains:
  + **P-N junction**
  + **Active region**: where recombination occurs
  + **Metallic contacts** for current supply
  + **Polished facets** to reflect light and form an optical cavity (resonator)

**Diagram (Described):**

\_\_\_\_\_\_\_Metal Contact\_\_\_\_\_\_\_\_

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| P-type semiconductor |

|----------------------------| ← Junction (Active region)

| N-type semiconductor |

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Reflecting Facets (mirrors)

**Working:**

1. When forward biased, **electrons and holes recombine** in the active region.
2. Each recombination emits a **photon**.
3. Some photons stimulate more recombination → **stimulated emission**.
4. Reflecting facets amplify light through multiple passes.
5. Coherent laser light is emitted from one end.

**1. (ii) Photocurrent in P-N Diode and Solar Cell**

**Photocurrent in P-N Diode:**

* When light falls on a **reverse-biased p-n junction**, **electron-hole pairs** are generated.
* These are swept by the electric field, producing **photocurrent**.
* More light → more carriers → more current.

**Solar Cell:**

**Principle:**

Converts **light energy into electrical energy** using the **photovoltaic effect**.

**Construction:**

* A **thin p-n junction** made from **semiconductors** like silicon.
* **Transparent glass cover** and **antireflection coating** on top.

**Diagram (Described):**

[ Sunlight ]

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│ Transparent Layer│

│ P-type layer │

│------------------│ ← Junction

│ N-type layer │

│ Contact and Base │

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Load (electric circuit)

**Working:**

* Sunlight hits the junction → creates **electron-hole pairs**.
* The built-in electric field separates charges → generates **electric current**.
* Current flows through external load.

**2. Explain the principle and working of LED and OLED with a neat diagram.**

**Principle and Working of LED and OLED**

**(i) Light Emitting Diode (LED)**

**Principle:**

Based on **electroluminescence**: When forward biased, electrons recombine with holes and emit **visible light**.

**Construction:**

* Made using **direct bandgap semiconductors** (GaAs, GaP, InGaN).
* Consists of a **P-N junction** with **transparent packaging**.

**Diagram (Described):**

Anode (+)

|

[ Transparent Dome ]

| P-type material |

|-------------------| ← Junction

| N-type material |

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Cathode (–)

**Working:**

* Forward bias causes **recombination** in the junction.
* Energy is released in the form of **light**.
* Light color depends on the **bandgap** of the material.

**(ii) Organic Light Emitting Diode (OLED)**

**Principle:**

**Electroluminescence** in **organic compounds** — when current passes through an organic layer, light is emitted.

**Construction:**

* Layers:
  1. **Cathode**
  2. **Electron Transport Layer (ETL)**
  3. **Emissive Layer (Organic)**
  4. **Hole Transport Layer (HTL)**
  5. **Anode**

**Diagram (Described):**

[Glass Substrate]

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│ Anode │

│ Hole Transport Layer│

│ Emissive Layer │

│ Electron Transport │

│ Cathode │

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**Working:**

1. **Electrons** from cathode and **holes** from anode are injected into the organic layer.
2. They **recombine** in the emissive layer → emit **light**.
3. Light passes through transparent anode or substrate.

**Applications of LED and OLED:**

| **LED** | **OLED** |
| --- | --- |
| Indicators, TV remotes | Smartphones, TVs, Wearables |
| Decorative lighting | Flexible displays |
| Traffic signals, headlights | Transparent screens |

**Unit V NANO DEVICES**

**20. Briefly explain (i) Quantum systemfor information processing, (ii). Quantum states, (iii). Classical bits, (iv). Quantum bits**

**(i) Quantum System for Information Processing**

A quantum system for information processing uses the principles of quantum mechanics—like superposition, entanglement, and interference—to **store,** process, and transmit information.

* Traditional computers use **bits** (0 or 1), whereas quantum computers use **qubits** (quantum bits), which can be in **multiple states simultaneously**.
* **Quantum systems** can solve certain problems **faster** than classical systems.  
  Examples include **Shor’s algorithm** (for factoring) and **Grover’s algorithm** (for search).

**Advantages:**

* Exponential speed-up in some computations
* Enhanced **security** in communication (Quantum Cryptography)

**(ii) Quantum States**

A **quantum state** describes the **condition** of a quantum system. It is typically represented by a **ket notation**:

∣ψ⟩=α∣0⟩+β∣1⟩|\psi\rangle = \alpha|0\rangle + \beta|1\rangle

Where:

* ∣0⟩|0\rangle and ∣1⟩|1\rangle are **basis states**
* α\alpha and β\beta are complex numbers (called **probability amplitudes**)
* ∣α∣2+∣β∣2=1|\alpha|^2 + |\beta|^2 = 1

Quantum states can exhibit:

* **Superposition**: Being in a combination of multiple states
* **Entanglement**: Correlated states of two or more particles

**(iii) Classical Bits**

A **classical bit** is the basic unit of information in **classical computing**. It can exist in only **one of two definite states**:

Bit=0or1\text{Bit} = 0 \quad \text{or} \quad 1

Characteristics:

* Represented using voltage levels (e.g., 0V = 0, 5V = 1)
* Processed using logic gates (AND, OR, NOT)
* Deterministic behavior

**(iv) Quantum Bits (Qubits)**

A **qubit** is the fundamental unit of information in **quantum computing**. Unlike classical bits, a qubit can be in a **superposition** of both 0 and 1 at the same time:

∣ψ⟩=α∣0⟩+β∣1⟩|\psi\rangle = \alpha|0\rangle + \beta|1\rangle

Where:

* α,β\alpha, \beta are complex numbers
* ∣α∣2+∣β∣2=1|\alpha|^2 + |\beta|^2 = 1 ensures normalization

**Properties:**

* **Superposition** allows parallel computation
* **Entanglement** allows information sharing across qubits
* **Measurement** collapses qubit into either 0 or 1

**Comparison Table:**

| **Feature** | **Classical Bit** | **Quantum Bit (Qubit)** |
| --- | --- | --- |
| States | 0 or 1 | 0, 1, or both (superposition) |
| Processing | Deterministic | Probabilistic/Quantum gates |
| Memory usage | Linear | Exponential potential |
| Example system | Classical CPU | Quantum computer (IBM Q, etc) |

**2. Explain in detail about tunneling process and also give an account on resonant tunneling diode with neat diagram.**

**2. (i) Tunneling Process**

**Definition:**

**Quantum tunneling** is a phenomenon where a particle penetrates through a **potential energy barrier** even if its energy is **less than** the height of the barrier. This is **not possible** in classical physics but occurs in quantum mechanics due to the **wave nature** of particles.

**Explanation:**

* According to Schrödinger's equation, the **wavefunction** of a particle doesn't go to zero abruptly at a barrier—it **decays exponentially**.
* There's a **non-zero probability** that the particle appears on the other side of the barrier.

**Diagram (Described):**

Potential Barrier

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E < V | | ← Barrier (height V)

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Tunneling Particle detected

* A particle with energy EE approaches a barrier of height V>EV > E
* Instead of being reflected completely, it **tunnels** through
* Observed in devices like **Tunnel Diodes** and **RTDs**

**Applications:**

* Tunnel diodes
* Flash memory
* Scanning Tunneling Microscope (STM)
* Nuclear fusion (quantum tunneling of particles)

**(ii) Resonant Tunneling Diode (RTD)**

**What is RTD?**

A **Resonant Tunneling Diode** is a quantum device that uses the **resonant tunneling effect** to allow electrons to pass through **multiple barriers** at certain energy levels.

**Structure:**

* Made of a **quantum well** sandwiched between two **barriers**.
* Materials: Typically **GaAs/AlAs** heterostructure.

**Diagram (Described):**

Energy Band Diagram:

Barrier Well Barrier

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→ Electron tunnels only when energy matches the well level

* **Quantum Well**: A thin layer where electron energy levels are discrete
* **Barriers**: Prevent electrons from passing freely
* At **resonant energy**, electron transmission is high

**Working Principle:**

1. **At low voltage**:
   * Electrons do not have enough energy → no current
2. **At resonant voltage**:
   * Electron energy matches energy level in the well → **maximum tunneling current**
3. **Beyond this voltage**:
   * No resonance → current **drops** → **negative differential resistance (NDR)**

**I-V Characteristics:**

* Shows a **peak current** at resonance
* After that, **current decreases** (NDR region)
* Then increases again due to normal conduction

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I | /\

| / \ ← Peak current

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| \→ (NDR)

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**Applications of RTD:**

* **High-speed oscillators**
* **Frequency multipliers**
* **Memory and logic circuits**
* **THz applications**

**Advantages:**

* Operates at **very high speed** (THz range)
* **Small size** and power efficiency

**Conclusion:**

The **tunneling process** is a fundamental quantum effect that enables the operation of devices like RTDs. The **resonant tunneling diode** utilizes this effect with engineered quantum wells to exhibit **unique electrical characteristics**, including **negative differential resistance**, useful in high-speed electronic applications.