Information Electronics Physics Fundamentals

Lecture Notes

Abstract

This document serves as a summarized translation of the lecture notes for "Information Electronics Physics Fundamentals". It covers Solid State Types, Quantum Mechanics Basics, Band Theory, Carrier Transport, and PN Junction/Semiconductor Device Physics.

Contents

1 Solid State Types and Crystal Structure **3**
- 1.1 Types of Solids 3
- 1.2 Space Lattice 3
  - 1.2.1 Unit Cells 3
- 1.3 Basic Crystal Structures 3
  - 1.3.1 Diamond Structure 4
- 1.4 Crystal Planes and Miller Indices 4
- 1.5 Defects and Impurities 4

2 Quantum Mechanics Basics **6**
- 2.1 Wave-Particle Duality 6
- 2.2 The Schrödinger Equation 6
  - 2.2.1 Physical Meaning of ψ 6
- 2.3 Applications 6
  - 2.3.1 Infinite Potential Well 6
  - 2.3.2 Potential Barrier and Tunneling 6
- 2.4 Atomic Theory 7

3 Band Theory and Carrier Transport **8**
- 3.1 Energy Band Formation 8
- 3.2 Classifications of Solids 8

3.3 Effective Mass and Holes . . . 8
3.4 Carrier Concentration . . . 9
3.4.1 Fermi-Dirac Distribution . . . 9
3.4.2 Equilibrium Concentrations . . . 9
3.5 Doping . . . 9
3.6 Transport Properties . . . 9

4 PN Junctions and Semiconductor Devices **10**
4.1 The PN Junction at Equilibrium . . . 10
4.2 Biasing the PN Junction . . . 10
4.3 Junction Capacitance . . . 10
4.4 Breakdown Mechanisms . . . 11
4.5 Metal-Semiconductor Contacts . . . 11
4.6 Heterojunctions . . . 11

5 Optical Properties of Solids and Optoelectronics **11**
5.1 Optical Absorption . . . 11
5.1.1 Absorption Coefficient . . . 12
5.1.2 Direct and Indirect Transitions . . . 12
5.2 Photovoltaic Effect and Solar Cells . . . 12
5.2.1 Characteristics . . . 13
5.2.2 Advanced Structures . . . 13
5.3 Photodetectors . . . 13
5.3.1 Non-Gain Detectors (Photodiodes) . . . 13
5.3.2 Gain Detectors (Avalanche Photodiodes - APD) . . . 14
5.4 Light Emission (LEDs and Lasers) . . . 14
5.4.1 Light Emitting Diodes (LED) . . . 14
5.4.2 Laser Diodes (LD) . . . 14

6 Magnetoelectronics **15**
6.1 Magnetic Properties of Materials . . . 15
6.2 Ferromagnetism and Hysteresis . . . 15

7 Superconductivity **16**
7.1 Basic Properties . . . 16
7.2 Critical Parameters . . . 16
7.3 Types of Superconductors . . . 16
7.4 Theoretical Models . . . 16
7.4.1 London Equations . . . 16
7.4.2 BCS Theory (Bardeen-Cooper-Schrieffer) . . . 16
7.5 Tunneling and Josephson Effect . . . 17

1 Solid State Types and Crystal Structure

1.1 Types of Solids

Solids are classified based on the arrangement of their atoms:

- **Amorphous:** Short-range order only (no long-range periodicity).
- **Polycrystalline:** Composed of many small crystallites or grains.
- **Single Crystal:** Long-range order extends throughout the entire material. This is crucial for semiconductor devices.

1.2 Space Lattice

A crystal structure is described by:

$$\text{Crystal Structure} = \text{Lattice} + \text{Basis} \tag{1}$$

- **Lattice:** A set of points (grid) where every point has an identical environment.
- **Basis:** An atom or group of atoms attached to every lattice point.
- **Bravais Lattices:** 14 unique lattice structures in 3D space where all lattice points are equivalent.

1.2.1 Unit Cells

- **Primitive Cell:** The smallest volume cell that can reproduce the lattice (contains 1 lattice point). Vectors: $\vec{a}, \vec{b}, \vec{c}$.
- **Unit Cell:** A convenient repeating volume (may contain > 1 lattice point) chosen to display symmetry.
- **Lattice Constant (a):** The physical dimension of the unit cell side length. Typical magnitude: 10^{-8} cm or 1 Å.

1.3 Basic Crystal Structures

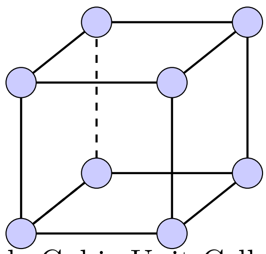
Common structures in cubic systems:

1. **Simple Cubic (SC):** Atoms at corners only.
2. **Body-Centered Cubic (BCC):** Atoms at corners + 1 atom in the center.
3. **Face-Centered Cubic (FCC):** Atoms at corners + atoms at the center of each face.

1.3.1 Diamond Structure

Crucial for Silicon (Si) and Germanium (Ge).

- Can be visualized as two interpenetrating FCC sub-lattices shifted by a diagonal vector $(\frac{1}{4}, \frac{1}{4}, \frac{1}{4})$.
- Each atom has 4 nearest neighbors (tetrahedral bonding).
- Nearest neighbor distance: $\frac{\sqrt{3}}{4}a$.



Simple Cubic Unit Cell

1.4 Crystal Planes and Miller Indices

To determine the Miller indices (hkl) of a plane:

1. Find intercepts on axes in terms of lattice constants (e.g., p, q, r).
2. Take reciprocals $(\frac{1}{p}, \frac{1}{q}, \frac{1}{r})$.
3. Reduce to the smallest integers.

Note: For cubic systems, direction $[hkl]$ is perpendicular to plane (hkl).

1.5 Defects and Impurities

Real crystals deviate from perfect periodicity.

- **Thermal Vibration:** Atoms vibrate around equilibrium positions.
- **Point Defects:**
  - *Vacancy:* An atom is missing from a lattice site.
  - *Interstitial:* An atom is squeezed into a void between sites.
  - *Frenkel Defect:* Pair of Vacancy + Interstitial (atom moves to interstitial site).
  - *Schottky Defect:* Atom moves from interior to the surface, leaving a vacancy. Requires less energy than Frenkel.
- **Impurities (Doping):**

- *Substitutional:* Impurity replaces a host atom.
- *Interstitial:* Impurity sits in voids.
- *Ion Implantation:* High-energy method to introduce impurities (precise but damages lattice).
- *Diffusion:* Thermal movement from high to low concentration.

2 Quantum Mechanics Basics

2.1 Wave-Particle Duality

- **Energy Quanta:** $E = h\nu = \hbar\omega$.
- **Momentum:** $p = \frac{h}{\lambda} = \hbar k$.
- **Heisenberg Uncertainty Principle:** $\Delta x \Delta p \geq \frac{\hbar}{2}$.

2.2 The Schrödinger Equation

The fundamental equation governing the behavior of electrons.

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(x,t) + U(x)\Psi(x,t) = j\hbar\frac{\partial\Psi(x,t)}{\partial t} \tag{2}$$

For a time-independent potential $U(x)$, the wavefunction separates into spatial and temporal parts. The time-independent form is:

$$\frac{d^2\psi(x)}{dx^2} + \frac{2m}{\hbar^2}(E - U(x))\psi(x) = 0 \tag{3}$$

2.2.1 Physical Meaning of ψ

- $\psi(x)$ itself is a complex quantity with no direct physical meaning.
- $|\psi(x)|^2 = \psi(x)\psi^*(x)$ represents the **probability density** of finding the electron at position x.
- Normalization condition: $\int_{-\infty}^{\infty} |\psi(x)|^2 dx = 1$.

2.3 Applications

2.3.1 Infinite Potential Well

Electron confined in region $0 < x < a$ with $U(x) = 0$, and $U(x) = \infty$ elsewhere.

- Solution: $\psi_n(x) = \sqrt{\frac{2}{a}} \sin\left(\frac{n\pi x}{a}\right)$.
- Energy is quantized: $E_n = \frac{\hbar^2\pi^2 n^2}{2ma^2}$ where $n = 1, 2, 3...$

2.3.2 Potential Barrier and Tunneling

When an electron with energy $E < U_0$ encounters a potential barrier of finite width:

- Classically: Reflection $R = 1$.

- Quantum Mechanically: The wavefunction decays exponentially inside the barrier but is non-zero on the other side.
- **Tunneling Effect:** There is a finite probability of transmission.

2.4 Atomic Theory

For a single electron atom (Hydrogen model), states are defined by quantum numbers:

- **Principal (n):** Energy shell ($n = 1, 2...$).
- **Orbital (l):** Angular momentum ($l = 0, 1...n - 1$).
- **Magnetic (m):** Orientation ($m = -l... + l$).
- **Spin (s):** Intrinsic property ($s = \pm 1/2$).

3 Band Theory and Carrier Transport

3.1 Energy Band Formation

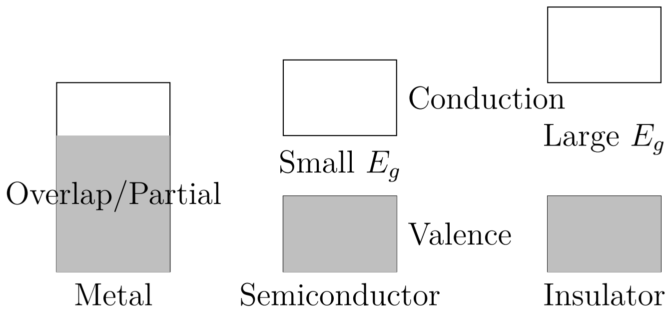
As atoms are brought together to form a crystal, discrete atomic energy levels split into continuous bands due to the interaction of wavefunctions (Pauli Exclusion Principle).

- **Bloch Theorem:** In a periodic potential, the wavefunction is a plane wave modulated by a periodic function: $\psi(x) = u(x)e^{jkx}$.
- **Kronig-Penney Model:** Uses a periodic square well potential to mathematically demonstrate the existence of allowed energy bands and forbidden gaps.

3.2 Classifications of Solids

Based on band structure at 0K:

- **Insulator:** Filled valence band, empty conduction band, large band gap (E_g).
- **Semiconductor:** Similar to insulators but small E_g. Electrons can be thermally excited.
- **Metal:** Partially filled band or overlapping conduction/valence bands.



3.3 Effective Mass and Holes

- Electrons in a crystal respond to external forces as if they had a mass m^*, different from vacuum mass m_0.
- $m^* = \hbar^2 \left(\frac{d^2E}{dk^2}\right)^{-1}$. Curvature of the band determines mass.
- **Hole:** A missing electron in the valence band behaves like a positively charged particle with positive effective mass.

3.4 Carrier Concentration

3.4.1 Fermi-Dirac Distribution

The probability that a state at energy E is occupied:

$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)} \tag{4}$$

Where E_F is the Fermi Level. At $T = 0\text{K}$, $f(E) = 1$ for $E < E_F$ and 0 for $E > E_F$.

3.4.2 Equilibrium Concentrations

- Electron conc. (n_0): $n_0 = N_c \exp\left(-\frac{E_c - E_F}{k_B T}\right)$
- Hole conc. (p_0): $p_0 = N_v \exp\left(-\frac{E_F - E_v}{k_B T}\right)$
- **Law of Mass Action:** $n_0 p_0 = n_i^2 = N_c N_v \exp\left(-\frac{E_g}{k_B T}\right)$. This holds independent of doping in equilibrium.
- **Intrinsic Fermi Level (E_i):** Located near the middle of the band gap.

3.5 Doping

- **Donors (N-type):** Group V elements (e.g., P, As in Si). Add electrons. Level E_D near E_c.
- **Acceptors (P-type):** Group III elements (e.g., B in Si). Create holes. Level E_A near E_v.
- **Temperature Regimes:**
  1. *Freeze-out (Low T):* Dopants not fully ionized.
  2. *Extrinsic (Medium T):* Constant carrier density determined by doping ($n \approx N_D$).
  3. *Intrinsic (High T):* Thermally generated carriers dominate ($n_i > N_D$).

3.6 Transport Properties

- **Drift:** Motion caused by electric field. $v_d = \mu E$. (μ = mobility).
- **Resistivity:** $\rho = \frac{1}{\sigma} = \frac{1}{q(n\mu_n + p\mu_p)}$.
- **Hall Effect:** Used to measure carrier type and concentration.
  - N-type: Hall coefficient $R_H < 0$.
  - P-type: Hall coefficient $R_H > 0$.

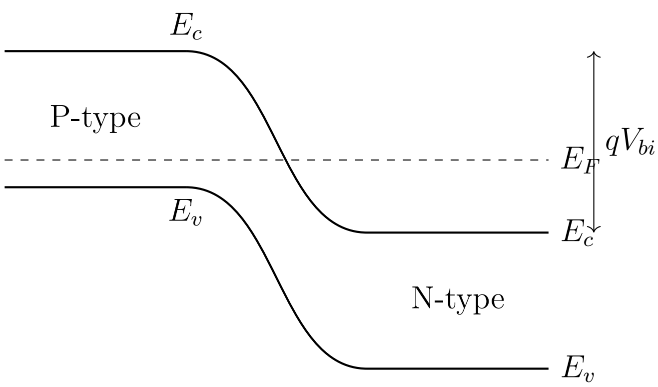
4 PN Junctions and Semiconductor Devices

4.1 The PN Junction at Equilibrium

When P-type and N-type materials join:

- **Diffusion:** Holes diffuse $P \to N$, Electrons diffuse $N \to P$.
- **Space Charge Region (SCR):** Leaving behind ionized dopants (N_A^- in P-side, N_D^+ in N-side) creates a built-in electric field preventing further diffusion.
- **Energy Bands:** The Fermi level must be constant ($E_{FP} = E_{FN}$). This causes bands to bend.
- **Built-in Potential (V_{bi} or V_D):**

$$V_{bi} = \frac{k_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \tag{5}$$



4.2 Biasing the PN Junction

- **Forward Bias ($V_F > 0$):** P connected to (+). Barrier lowers. Diffusion current dominates.
- **Reverse Bias ($V_R > 0$):** P connected to (-). Barrier increases. Current is negligible (leakage).
- **Shockley Diode Equation:**

$$I = I_s \left[\exp\left(\frac{qV}{k_B T}\right) - 1\right] \tag{6}$$

4.3 Junction Capacitance

- **Barrier/Junction Capacitance (C_j):** Dominant in reverse bias. Acts like a parallel plate capacitor with changing width W. Used in **Varactor Diodes**.
- **Diffusion Capacitance (C_d):** Dominant in forward bias due to stored minority carriers.

4.4 Breakdown Mechanisms

Occurs at high reverse voltage.

1. **Zener Breakdown:** Tunneling of electrons from valence band to conduction band in heavily doped junctions.
2. **Avalanche Breakdown:** Impact ionization. Carriers gain enough kinetic energy to knock bound electrons free, creating pairs.

4.5 Metal-Semiconductor Contacts

- **Schottky Contact:** Rectifying (diode-like). Occurs when work functions differ such that a barrier forms ($\Phi_m > \Phi_s$ for n-type).
- **Ohmic Contact:** Linear I-V curve. Achieved by heavy doping (tunneling) or matching work functions. Essential for connecting devices to circuits.

4.6 Heterojunctions

Junctions between two different semiconductor materials (e.g., GaAs / AlGaAs).

- **Band Offsets:** Discontinuities in conduction (ΔE_c) and valence (ΔE_v) bands.
- **Quantum Wells:** Can trap carriers in 2D layers (2D Electron Gas).
- Applications: High Electron Mobility Transistors (HEMTs), Lasers.

5 Optical Properties of Solids and Optoelectronics

5.1 Optical Absorption

When light interacts with a solid, photons may be absorbed if their energy matches available energy states in the material.

- **Condition for Fundamental Absorption:** $h\nu \geq E_g$.
- **Process:** An electron in the valence band absorbs a photon and transitions to the conduction band, creating an electron-hole pair.
- **Transparency:** If $h\nu < E_g$, the material is typically transparent (ignoring impurities or phonon absorption).

5.1.1 Absorption Coefficient

The intensity of light $I(x)$ decays as it propagates through the material according to the Beer-Lambert Law:

$$I(x) = I_0 e^{-\alpha x} \tag{7}$$

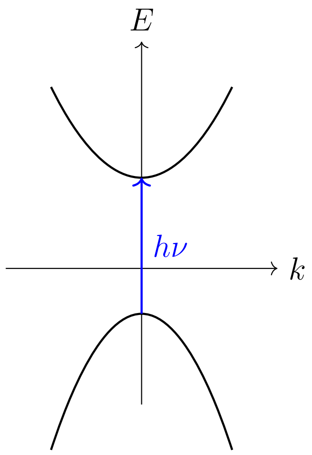
Where α is the absorption coefficient.

- Relation to complex refractive index $\tilde{n} = n + jk$: $\alpha = \frac{4\pi k}{\lambda_0}$.
- **Penetration Depth:** The distance $1/\alpha$ where intensity drops to $1/e$.

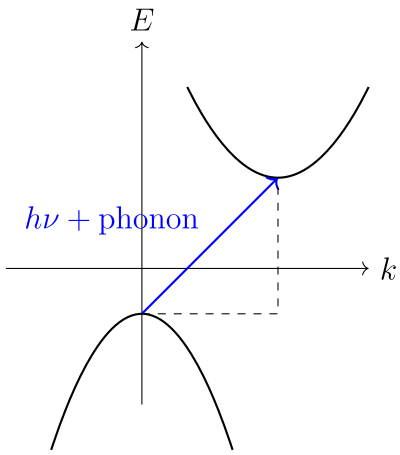
5.1.2 Direct and Indirect Transitions

Conservation of energy and crystal momentum ($\hbar k$) must be satisfied.

1. **Direct Transition:** The conduction band minimum and valence band maximum occur at the same wavevector k (usually $k = 0$).
   - Momentum conservation: $k_f \approx k_i$ (since photon momentum is negligible).
   - Example materials: GaAs, InP (efficient for LEDs/Lasers).
2. **Indirect Transition:** The band edges are at different k values.
   - Requires a **phonon** (lattice vibration) to conserve momentum: $E_f = E_i + h\nu \pm E_{phonon}$ and $\vec{k}_f = \vec{k}_i + \vec{q}_{phonon}$.
   - Less efficient process. Example material: Si, Ge.



Direct Bandgap



Indirect Bandgap

5.2 Photovoltaic Effect and Solar Cells

Solar cells operate on the photovoltaic effect within a PN junction.

- **Mechanism:** Photogenerated electron-hole pairs in the depletion region are separated by the built-in electric field (Electrons $\rightarrow$ N-side, Holes $\rightarrow$ P-side).

- This accumulation creates a forward voltage (photovoltage) opposing the built-in potential.

5.2.1 Characteristics

- **Short Circuit Current (I_{SC}):** Current when $V = 0$. Proportional to light intensity.
- **Open Circuit Voltage (V_{OC}):** Voltage when $I = 0$.
- **Fill Factor (FF):** A measure of "squareness" of the I-V curve.

$$FF = \frac{I_m V_m}{I_{SC} V_{OC}} \tag{8}$$

- **Efficiency (η):** Ratio of max electrical power output to incident optical power (P_{in}).

$$\eta = \frac{P_{max}}{P_{in}} = \frac{FF \cdot I_{SC} \cdot V_{OC}}{P_{in}} \tag{9}$$

5.2.2 Advanced Structures

- **Heterojunctions:** Using a wide bandgap material (e.g., AlGaAs) on top of a narrower one (GaAs). The top layer acts as a "window," allowing high-energy photons to reach the active region without surface recombination.
- **PIN Structure (Amorphous Si):** An intrinsic (i) layer is sandwiched between p and n layers to extend the electric field region, improving carrier collection efficiency in materials with low diffusion lengths.

5.3 Photodetectors

5.3.1 Non-Gain Detectors (Photodiodes)

Operate in reverse bias to widen the depletion region and increase speed.

- **Quantum Efficiency (η):** Number of electron-hole pairs generated per incident photon.
- **Responsivity (R):** Photocurrent per unit optical power (A/W).
- **PIN Photodiode:** The intrinsic layer width W can be tailored to optimize quantum efficiency (absorption volume) and response speed (transit time vs. capacitance).

5.3.2 Gain Detectors (Avalanche Photodiodes - APD)

Operate at high reverse bias near breakdown.

- **Mechanism:** Primary photogenerated carriers gain sufficient kinetic energy to cause *impact ionization*, creating secondary pairs.
- **Result:** Internal gain M. High sensitivity but higher noise.

5.4 Light Emission (LEDs and Lasers)

5.4.1 Light Emitting Diodes (LED)

- Based on **Spontaneous Emission**: An electron falls to the valence band randomly, emitting a photon.
- Operates in Forward Bias (carrier injection).
- Efficiency depends on the ratio of radiative to non-radiative recombination rates.

5.4.2 Laser Diodes (LD)

Based on **Stimulated Emission**: An incoming photon triggers an electron to drop, emitting an identical photon (same phase, frequency, direction). **Three Conditions for Lasing:**

1. **Population Inversion:** More electrons in the excited state than the ground state ($N_2 > N_1$). Achieved by heavy doping (degenerate) and high injection ($E_{Fc} - E_{Fv} > E_g$).
2. **Optical Cavity:** Fabry-Perot resonator (cleaved facets) provides feedback/amplification.
3. **Threshold Condition:** Gain $\geq$ Loss (absorption + mirror loss).

6 Magnetoelectronics

6.1 Magnetic Properties of Materials

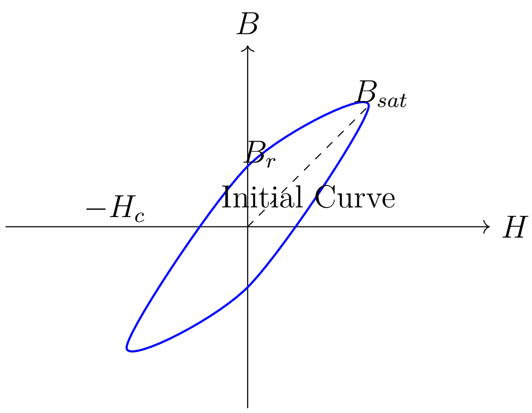
Magnetization M relates to magnetic field H via susceptibility χ: $M = \chi H$.

1. **Diamagnetism ($\chi < 0$):** Weak repulsion. Induced magnetic moment opposes external field (Lenz's law at atomic scale). Present in all matter but often masked.
2. **Paramagnetism ($\chi > 0$):** Weak attraction. Randomly oriented permanent dipoles align partially with the field.
3. **Ferromagnetism ($\chi \gg 0$):** Strong attraction. Spontaneous magnetization exists below the Curie Temperature (T_c).

6.2 Ferromagnetism and Hysteresis

Ferromagnetic materials exhibit a memory effect.

- **Domain Theory:** Below T_c, microscopic regions (domains) are fully magnetized. An external field aligns these domains.
- **Hysteresis Loop:** The relationship between B and H is non-linear and irreversible.
  - **Saturation (B_s):** All domains aligned.
  - **Remanence (B_r):** Magnetization remaining at $H = 0$.
  - **Coercivity (H_c):** Reverse field needed to demagnetize ($B = 0$).
- **Origin:** Quantum mechanical **Exchange Interaction** (Weiss Mean Field). The Pauli Exclusion Principle forces parallel spins in certain orbital overlaps to lower electrostatic energy.



7 Superconductivity

7.1 Basic Properties

1. **Zero Resistance:** Below a critical temperature T_c, DC electrical resistance vanishes ($R = 0$).

2. **Meissner Effect (Perfect Diamagnetism):** A superconductor expels all magnetic flux from its interior ($\chi = -1$). $B = 0$ inside.

7.2 Critical Parameters

Superconductivity is destroyed if any of these exceed their critical value:

- Temperature ($T > T_c$).
- Magnetic Field ($H > H_c$). Relationship: $H_c(T) \approx H_c(0)[1 - (T/T_c)^2]$.
- Current Density ($J > J_c$).

7.3 Types of Superconductors

- **Type I:** Abrupt transition from superconducting state to normal state at H_c. (Mostly pure metals).
- **Type II:** Exists in a "Mixed State" (or Vortex State) between H_{c1} and H_{c2}. Magnetic flux penetrates in quantized vortices. (Allows for high-field magnets).

7.4 Theoretical Models

7.4.1 London Equations

Phenomenological description of electromagnetic fields in superconductors. Predicts the **Penetration Depth** (λ_L), the thin surface layer where supercurrents flow to screen the magnetic field.

7.4.2 BCS Theory (Bardeen-Cooper-Schrieffer)

Microscopic quantum theory.

- **Cooper Pairs:** Electrons (fermions) pair up to form bosons with opposite spin and momentum.
- **Mechanism:** Electron-Phonon Interaction. An electron distorts the lattice (attracts positive ions), creating a region of excess positive charge that attracts a second electron.

- **Energy Gap (2Δ):** A gap forms at the Fermi level, preventing small excitations (scattering) which causes resistance. $2\Delta \approx 3.5 k_B T_c$.

7.5 Tunneling and Josephson Effect

- **Giaever Tunneling (SIS):** Tunneling of single electrons (quasiparticles) only occurs when voltage bias $eV \geq \Delta$ (or 2Δ for S-I-S), revealing the density of states gap.
- **Josephson Effect:** Tunneling of **Superconducting Cooper Pairs** through a thin insulating barrier.
  - **DC Josephson Effect:** Current flows with zero voltage drop ($V = 0$) up to a critical current I_c.
  - **AC Josephson Effect:** If a DC voltage V is applied, the current oscillates at frequency $f = 2eV/h$.