APPLIED PHYSICS 2

2nd Semester | Diploma / Polytechnic Engineering

UNIT – 6

Semiconductor Physics

Comprehensive Study Notes | Exam-Oriented | Diploma Level

1. Energy Bands in Solids

When atoms combine to form a solid, the discrete energy levels of individual atoms broaden into continuous ranges called energy bands. Understanding these bands is the foundation for explaining why some materials conduct electricity easily, while others do not. This concept is central to modern electronics and semiconductor technology.

1.1 Valence Band

The valence band is the range of energy levels occupied by the outermost electrons (valence electrons) of atoms in a solid at absolute zero temperature. These electrons are bound to their parent atoms and do not participate in electrical conduction under normal conditions.

- Completely filled at 0 K (absolute zero)
- Electrons here are tightly bound to atoms
- No free movement of electrons in this band
- Represents the ground state energy of outer electrons

1.2 Conduction Band

The conduction band is the energy band above the valence band. Electrons that gain sufficient energy can jump into this band, where they become free to move throughout the material and conduct electricity. The conduction band may be partially filled or completely empty.

- Electrons in this band are called free electrons or conduction electrons
- Responsible for electrical conductivity
- May be empty (insulators) or partially filled (conductors/semiconductors)
- Electrons here can move under an applied electric field

1.3 Band Gap (Forbidden Energy Gap)

The band gap, also known as the forbidden energy gap, is the energy difference between the top of the valence band and the bottom of the conduction band. No electrons can exist at these energy levels under normal conditions. The size of the band gap determines whether a material is a conductor, semiconductor, or insulator.

- **Band Gap Energy:** `Eg = Ec - Ev`
- Ec = Lowest energy level of conduction band
- Ev = Highest energy level of valence band
- For Conductors: Eg = 0 eV (bands overlap)
- For Semiconductors: Eg = 0.1 to 3 eV (e.g., Si = 1.1 eV, Ge = 0.67 eV)
- For Insulators: Eg > 5 eV (e.g., Diamond = 5.4 eV, Glass ~ 9 eV)

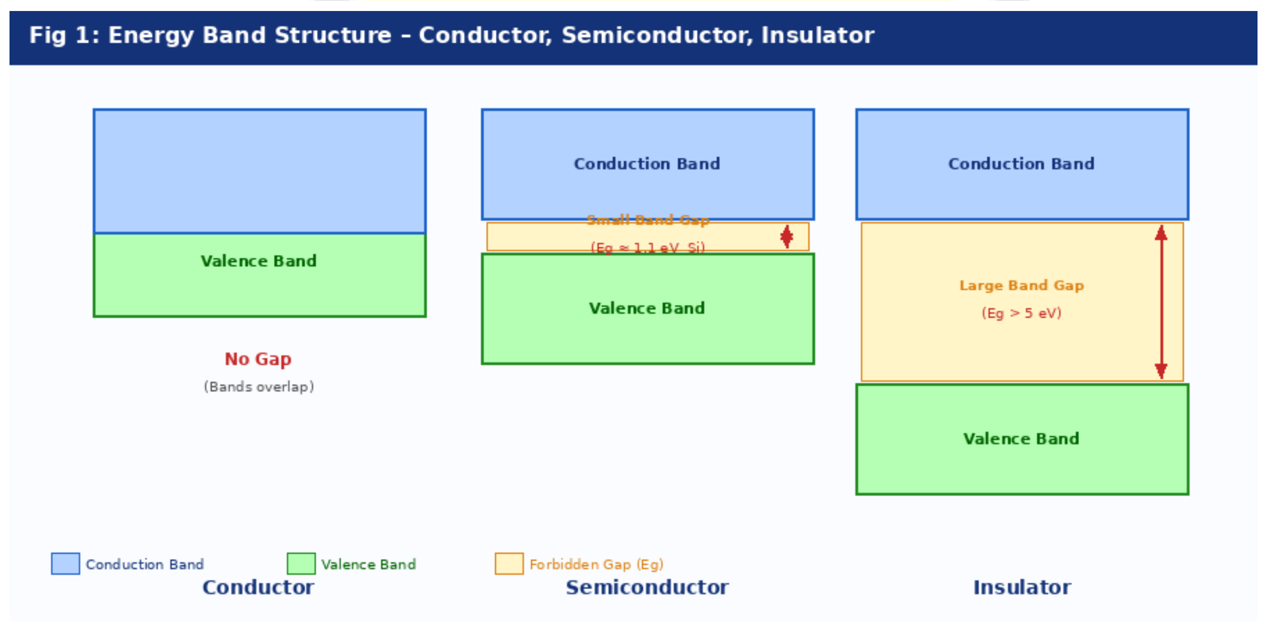

Fig 1: Energy Band Structure – Conductor (overlapping bands), Semiconductor (small gap ~1.1 eV), Insulator (large gap >5 eV)

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2. Types of Materials Based on Electrical Conductivity

Based on their energy band structure and electrical conductivity, materials are classified into three main categories: Conductors, Semiconductors, and Insulators. This classification helps engineers select the right material for specific applications.

2.1 Conductors

Conductors are materials that allow electricity to flow through them easily. In conductors, the valence band and conduction band either overlap or the conduction band is always partially filled. This means electrons can move freely without needing extra energy.

- Examples: Copper (Cu), Aluminium (Al), Silver (Ag), Gold (Au)
- Band gap = 0 eV (no forbidden gap)
- Resistivity: 10^-8 to 10^-6 ohm-m
- Conductivity decreases with increase in temperature (more lattice vibrations oppose electron flow)
- Applications: Electrical wiring, circuit connections, transformers

2.2 Insulators

Insulators are materials that do not allow electric current to flow under normal conditions. They have a very large band gap, making it nearly impossible for electrons to jump from the valence band to the conduction band. Even at high temperatures, very few electrons gain enough energy to cross this large gap.

- Examples: Glass, Rubber, Mica, Diamond, Plastics, Wood
- Band gap > 5 eV
- Resistivity: 10^10 to 10^18 ohm-m
- Conductivity does not change significantly with temperature
- Applications: Wire insulation, PCB substrates, transformer core insulation

2.3 Semiconductors

Semiconductors have electrical properties between conductors and insulators. Their band gap is small enough that electrons can be excited across it by thermal energy or light. Their conductivity increases with temperature, which is opposite to conductors. This unique property makes them ideal for electronic devices.

- Examples: Silicon (Si), Germanium (Ge), Gallium Arsenide (GaAs)
- Band gap: 0.1 to 3 eV (Si = 1.1 eV, Ge = 0.67 eV)
- Resistivity: 10^-4 to 0.5 ohm-m
- Conductivity increases with temperature
- Properties can be modified by adding impurities (doping)
- Applications: Transistors, diodes, solar cells, LEDs, ICs

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3. Semiconductors

3.1 Intrinsic Semiconductor

An intrinsic semiconductor is a pure semiconductor material with no intentional addition of impurity atoms. Silicon and Germanium are the most common intrinsic semiconductors. At absolute zero temperature (0 K), they behave like perfect insulators. As temperature increases, some electrons gain enough energy to cross the band gap and move to the conduction band, leaving behind holes in the valence band.

- Also called pure semiconductor
- Number of electrons (n) = Number of holes (p) at any temperature: n = p = ni
- ni is called the intrinsic carrier concentration
- Both electrons and holes act as charge carriers
- Conductivity is low at room temperature but increases with temperature
- **Intrinsic Carrier Concentration:** `ni = sqrt(Nc * Nv) * exp(-Eg / 2kT)`
- k = Boltzmann constant, T = Temperature in Kelvin, Eg = Band gap energy

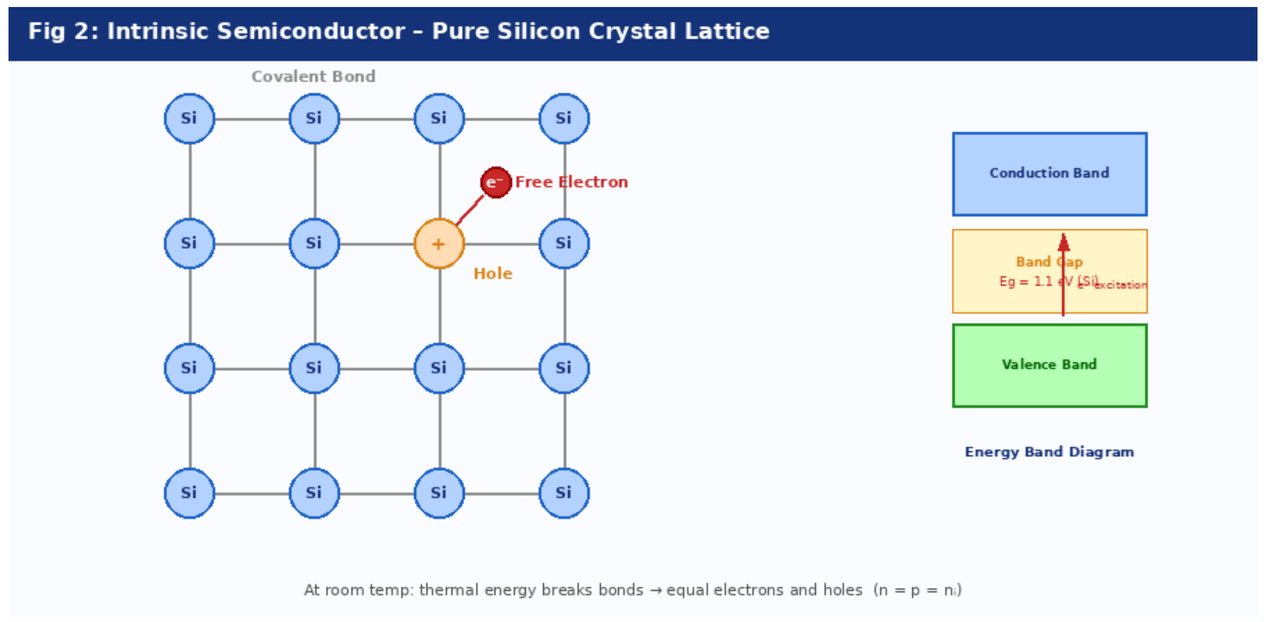

Fig 2: Intrinsic Semiconductor – Pure Si crystal lattice with a broken covalent bond showing free electron and hole generation at room temperature

3.2 Extrinsic Semiconductor

An extrinsic semiconductor is formed by deliberately adding a small amount of suitable impurity to an intrinsic semiconductor. This process is called doping, and the added impurity is called a dopant. Doping increases the conductivity significantly by increasing the number of either electrons or holes. There are two types of extrinsic semiconductors: n-type and p-type.

3.2.1 N-Type Semiconductor

N-type semiconductor is formed by doping a pure semiconductor (like Silicon) with a pentavalent impurity — an atom with 5 valence electrons. Elements like Phosphorus (P), Arsenic (As), and Antimony (Sb) are used as donors. Four of the five electrons form covalent bonds with neighboring Silicon atoms, while the fifth electron becomes a free electron available for conduction.

- Dopant: Pentavalent atoms (P, As, Sb) — called Donor atoms
- Majority charge carriers: Electrons (negative)
- Minority charge carriers: Holes
- Electron concentration >> Hole concentration: n >> p
- The Fermi level moves closer to the conduction band
- Material remains electrically neutral overall

3.2.2 P-Type Semiconductor

P-type semiconductor is formed by doping a pure semiconductor with a trivalent impurity — an atom with only 3 valence electrons. Elements like Boron (B), Gallium (Ga), and Indium (In) are used as acceptors. The three electrons form covalent bonds with neighboring Silicon atoms, but one bond is incomplete, creating a hole that can accept an electron.

- Dopant: Trivalent atoms (B, Ga, In) — called Acceptor atoms
- Majority charge carriers: Holes (positive)
- Minority charge carriers: Electrons
- Hole concentration >> Electron concentration: p >> n
- The Fermi level moves closer to the valence band
- Material remains electrically neutral overall

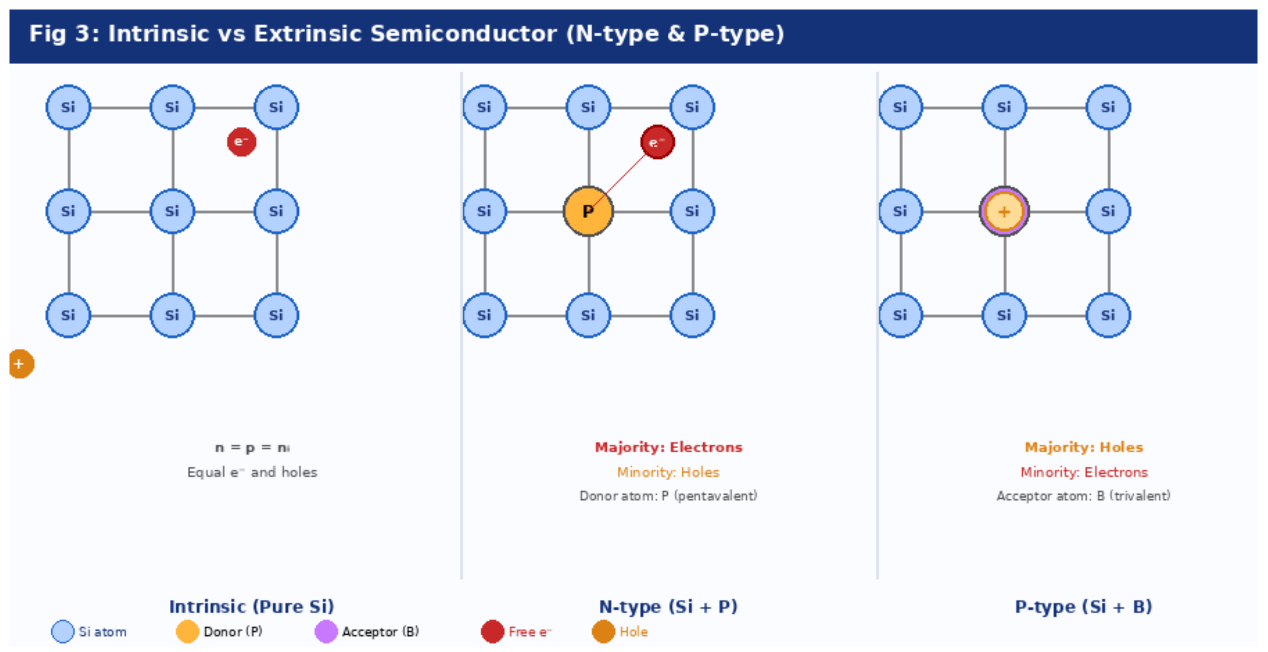

Fig 3: Intrinsic vs Extrinsic Semiconductor – Pure Si (equal carriers), N-type Si with Phosphorus donor (extra free electron), P-type Si with Boron acceptor (hole created)

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4. The P-N Junction

4.1 Formation of P-N Junction

A p-n junction is formed when a p-type semiconductor is joined with an n-type semiconductor. In practice, this is achieved by doping one side of a single semiconductor crystal with acceptor impurities and the other side with donor impurities. When the two regions come in contact, electrons from the n-side diffuse toward the p-side (where holes are majority carriers), and holes from the p-side diffuse toward the n-side.

This diffusion of carriers creates a region near the junction where there are very few free carriers — this is called the Depletion Region or Space Charge Region. In this region, positive ions are left on the n-side (because donor electrons have moved away) and negative ions are left on the p-side (because acceptor holes have been filled). This creates a built-in electric field pointing from n to p, which opposes further diffusion.

- Depletion Region: A thin layer (~0.5 to 1 micrometer) at the junction with no free carriers
- Built-in Potential (Barrier Potential): ~0.3 V for Ge, ~0.7 V for Si
- The built-in electric field prevents further diffusion at equilibrium
- No net current flows at thermal equilibrium

4.2 Working of P-N Junction

The behavior of a p-n junction changes depending on the polarity of the applied voltage (forward or reverse bias).

Forward Bias

When the positive terminal of a battery is connected to the p-side and the negative terminal to the n-side, the junction is forward biased. This reduces the depletion region and the built-in potential, allowing majority carriers to cross the junction easily. A large current flows through the junction.

- Depletion region narrows
- Barrier potential decreases
- Large forward current flows
- Diode acts like a closed switch (low resistance)

Reverse Bias

When the positive terminal is connected to the n-side and the negative terminal to the p-side, the junction is reverse biased. This widens the depletion region and increases the barrier potential, blocking the flow of majority carriers. Only a very small reverse current (called leakage current) flows due to minority carriers.

- Depletion region widens
- Barrier potential increases
- Only very small reverse (leakage) current flows
- Diode acts like an open switch (high resistance)

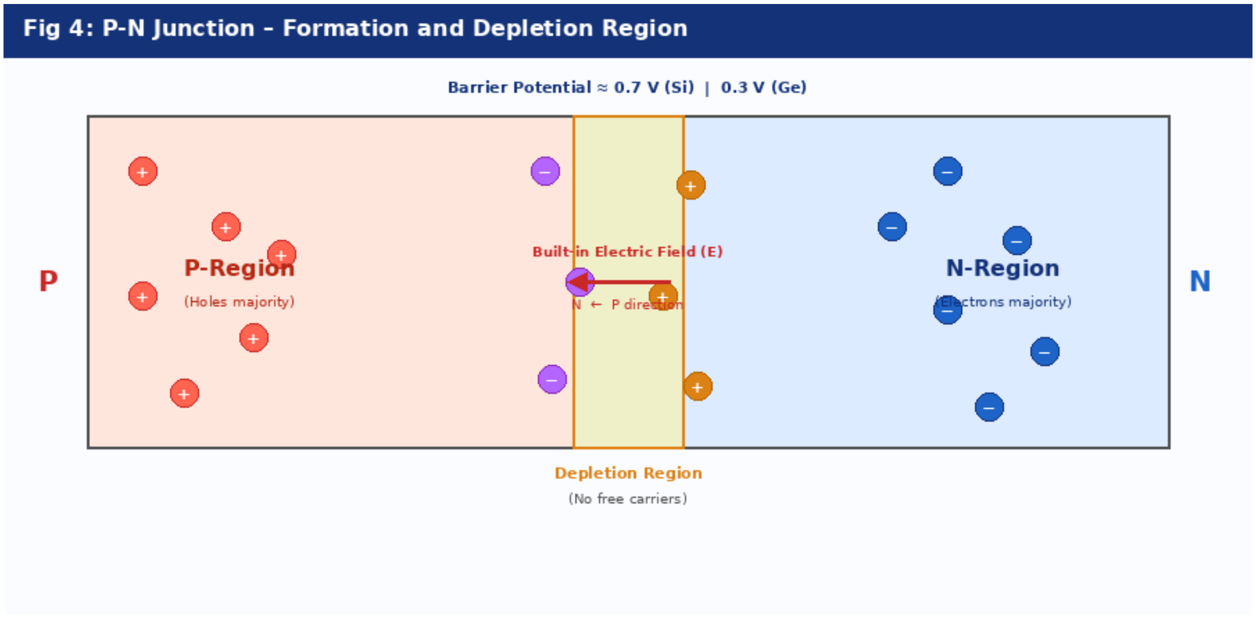

Fig 4: P-N Junction – Showing P-region (holes), N-region (electrons), depletion layer with fixed ions, and built-in electric field direction

5. Junction Diode and V-I Characteristics

5.1 Junction Diode

A junction diode is a two-terminal electronic device made from a p-n junction. It is the simplest semiconductor device and acts as a one-way valve for electric current — it allows current to flow easily in one direction (forward bias) but blocks it in the reverse direction. The two terminals are called Anode (p-side) and Cathode (n-side).

- Symbol: Arrow pointing from p to n, with a vertical bar at the cathode
- Anode (A): Connected to p-side
- Cathode (K): Connected to n-side
- Forward voltage for Si diode: ~0.7 V; for Ge diode: ~0.3 V

5.2 V-I Characteristics

The V-I (Voltage-Current) characteristic curve shows the relationship between the voltage applied across a diode and the resulting current through it. It has two distinct regions: forward bias and reverse bias.

Forward Bias Region:

- For Si diode, current starts flowing significantly above 0.7 V (cut-in voltage or threshold voltage)

- Current increases exponentially with voltage after the threshold
- Diode Equation: I = Io * (e^(V/nVT) - 1), where Io = reverse saturation current, VT = thermal voltage (~26 mV at room temp), n = ideality factor

Reverse Bias Region:

- Very small reverse current (micro-amperes) flows due to minority carriers — called reverse saturation current (Io)
- At a certain high reverse voltage (breakdown voltage), current suddenly increases — this is called Zener breakdown or avalanche breakdown
- For normal diodes, operation in breakdown region is avoided

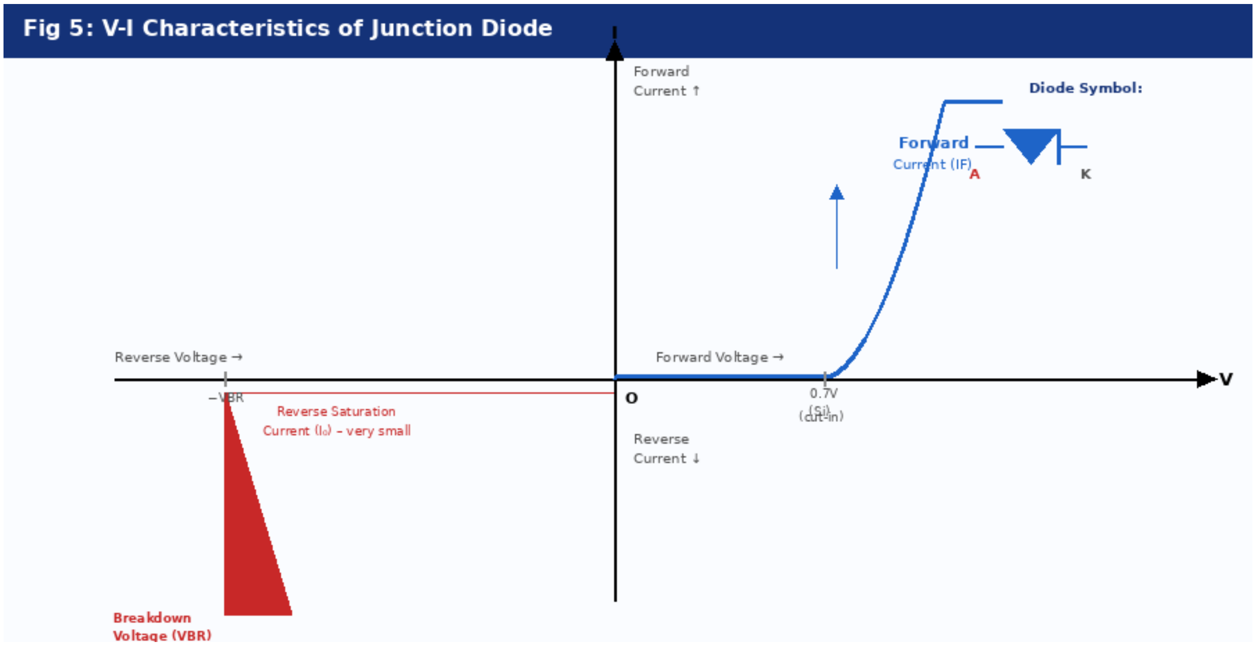

Fig 5: V-I Characteristics of Junction Diode – Forward bias (exponential rise after cut-in voltage), Reverse bias (small saturation current, sharp breakdown)

6. Diode as a Rectifier

A rectifier is a circuit that converts AC (alternating current) into DC (direct current). Since a diode conducts in only one direction, it can be used to convert the alternating voltage from a transformer into a unidirectional (DC) output. Rectifiers are widely used in power supply circuits for all electronic equipment.

6.1 Half Wave Rectifier

A half wave rectifier uses only a single diode. During the positive half cycle of the AC input, the diode is forward biased and conducts, allowing current to flow through the load resistor. During the negative half cycle, the diode is reverse biased and no current flows. The output is a pulsating DC that consists of only the positive half cycles of the input.

- Only one diode required — simple and cheap circuit
- Only 50% of the input AC signal is utilized (positive half only)
- **DC Output Voltage (Average):** `Vdc = Vm / pi  (where Vm = Peak voltage)`
- **Ripple Factor:** `r = 1.21 (high ripple — poor DC quality)`
- **Efficiency:** `eta = 40.6%`
- Applications: Battery charging, signal demodulation in AM radio receivers
- Disadvantage: High ripple, low efficiency, requires large filter capacitor

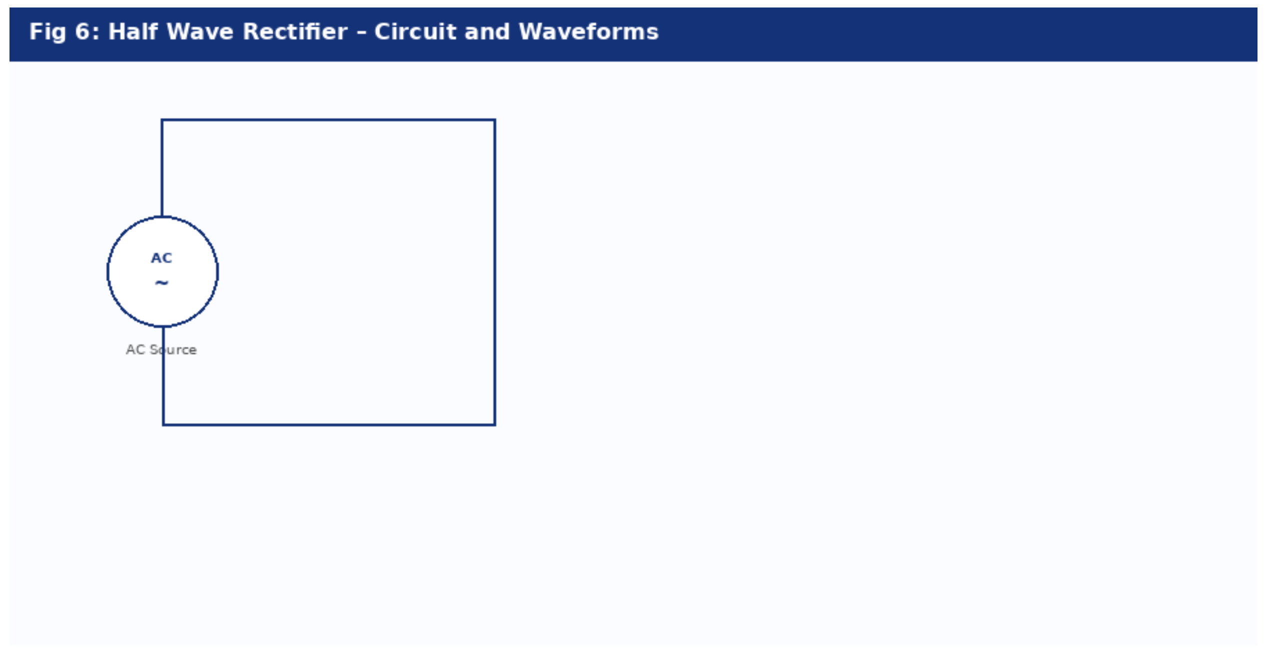

Fig 6: Half Wave Rectifier – Single diode circuit, input AC waveform (full sine), output waveform (positive half cycles only, gaps in between)

6.2 Full Wave Rectifier (Centre Tapped)

A full wave rectifier (centre tap type) uses two diodes and a centre-tapped transformer. The centre tap divides the secondary winding into two equal halves. During the positive half cycle, D1 conducts. During the negative half cycle, D2 conducts. This ensures that current flows through the load in the same direction during both half cycles, producing a smoother pulsating DC output.

- Two diodes (D1 and D2) and a centre-tapped transformer required
- Both half cycles of input AC are utilized
- **DC Output Voltage (Average):** `Vdc = 2Vm / pi`
- **Ripple Factor:** `r = 0.48 (better than half wave)`
- **Efficiency:** `eta = 81.2%`
- Ripple frequency = 2 × input frequency (100 Hz for 50 Hz input)
- Advantages: Better efficiency, lower ripple, smaller filter capacitor needed
- Disadvantage: Requires centre-tapped transformer (more complex and expensive)

- Applications: DC power supplies for radios, amplifiers, small electronic equipment

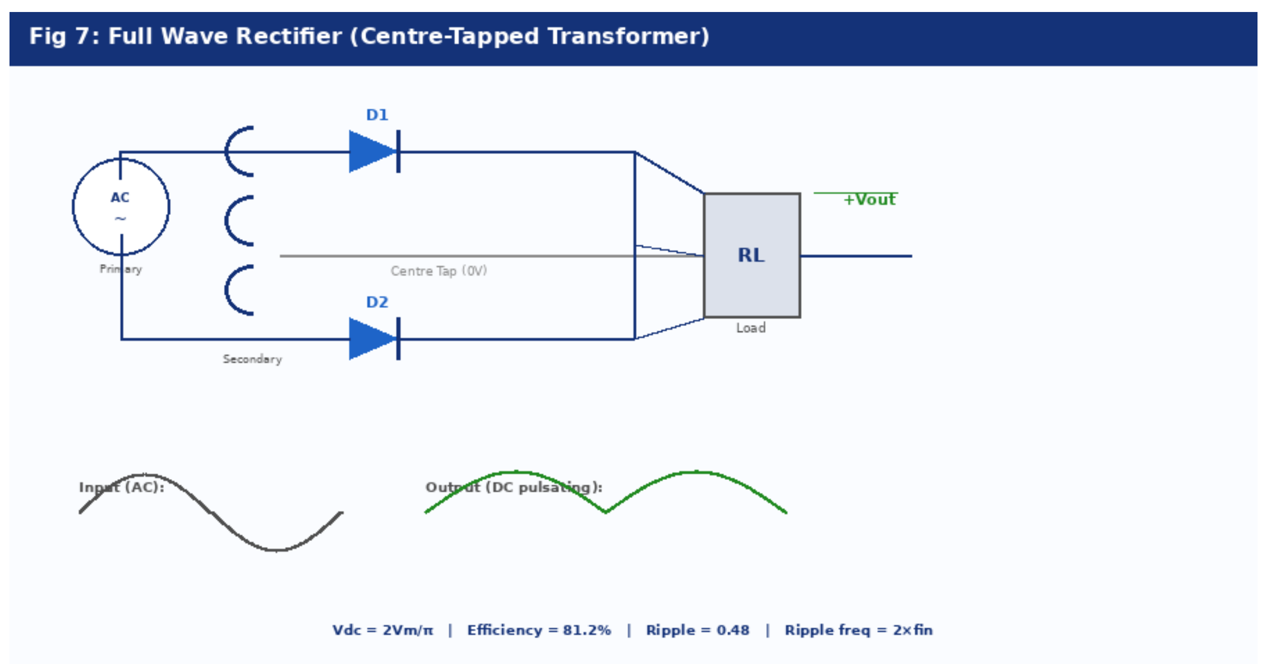

Fig 7: Full Wave Rectifier (Centre-Tapped) – Two diodes D1 & D2, centre-tap transformer, continuous pulsating DC output utilizing both AC half cycles

7. Transistor

7.1 Basic Concept

A transistor is a three-terminal semiconductor device that can amplify electrical signals or act as a switch. It is made by sandwiching one type of semiconductor between two layers of the opposite type. The three terminals are called Base (B), Emitter (E), and Collector (C). The transistor is the fundamental building block of modern electronic circuits and is found in virtually every electronic device.

- Terminal 1 — Emitter (E): Heavily doped, emits majority carriers
- Terminal 2 — Base (B): Very thin and lightly doped, controls carrier flow
- Terminal 3 — Collector (C): Moderately doped, collects carriers from the base
- The base region is very thin (~1 micrometer) — this is critical for transistor action

7.2 Types of Transistors

PNP Transistor

In a PNP transistor, a thin layer of n-type semiconductor (base) is sandwiched between two p-type semiconductor layers (emitter and collector). The majority carriers are holes. Current flows from emitter to collector when the base-emitter junction is slightly forward biased.

- Structure: P | N | P
- Majority carriers: Holes
- Conventional current flows from Emitter to Collector through Base
- Arrow on Emitter symbol points INWARD (toward the base) in circuit symbol

NPN Transistor

In an NPN transistor, a thin layer of p-type semiconductor (base) is sandwiched between two n-type semiconductor layers (emitter and collector). The majority carriers are electrons. This is the most commonly used transistor type in modern circuits.

- Structure: N | P | N
- Majority carriers: Electrons
- Conventional current flows from Collector to Emitter through Base
- Arrow on Emitter symbol points OUTWARD (away from base) in circuit symbol

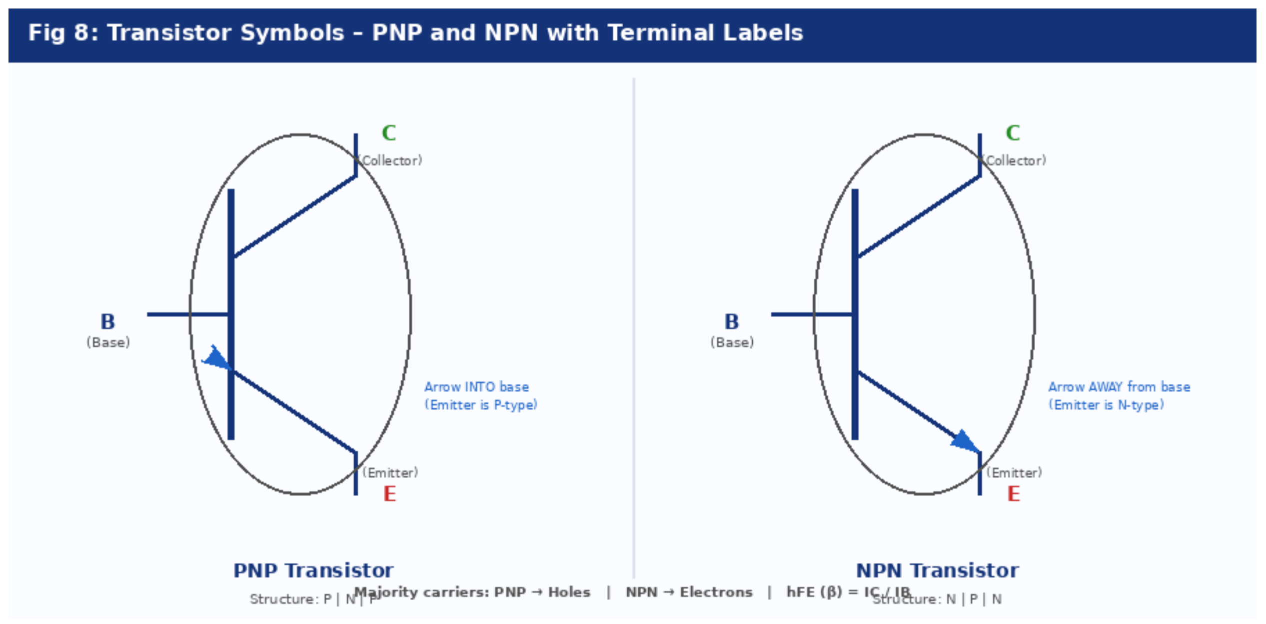

Fig 8: Transistor Circuit Symbols – PNP (arrow into base, holes majority) and NPN (arrow away from base, electrons majority) with terminals B, C, E labeled

8. Transistor as Amplifier (Common Emitter Mode)

8.1 Circuit Description

In the Common Emitter (CE) configuration, the emitter terminal is common to both the input (base-emitter) and output (collector-emitter) circuits. An NPN transistor is most commonly used. The input AC signal is applied between the base and emitter, and the amplified output is taken between the collector and emitter. A DC biasing supply (VCC) keeps the transistor in the active region.

- Input: Applied between Base (B) and Emitter (E)
- Output: Taken between Collector (C) and Emitter (E)
- VBB: DC bias supply for base (keeps transistor in active region)
- VCC: DC supply for collector circuit
- RC: Collector load resistor — output voltage developed across this
- RB: Base resistor — limits base current
- Cin, Cout: Coupling capacitors to block DC while passing AC signal

8.2 Working Principle

A small AC input signal applied to the base causes small variations in the base current (IB). Due to transistor action, a much larger variation appears in the collector current (IC), because IC = beta × IB, where beta (current gain, hFE) is typically 50 to 300 for common transistors. This large collector current variation across the load resistor RC produces a large amplified voltage at the output.

- **Current Gain (beta or hFE):** `beta = IC / IB`
- **Voltage Gain:** `Av = beta * (RC / Rin)`
- **Collector Current:** `IC = beta * IB  (approximately)`
- The output signal is 180 degrees out of phase with the input signal (phase reversal)
- CE mode gives the highest power gain among all transistor configurations
- Applications: Audio amplifiers, radio frequency amplifiers, signal boosters

Fig 9: NPN Transistor - Common Emitter Amplifier Circuit

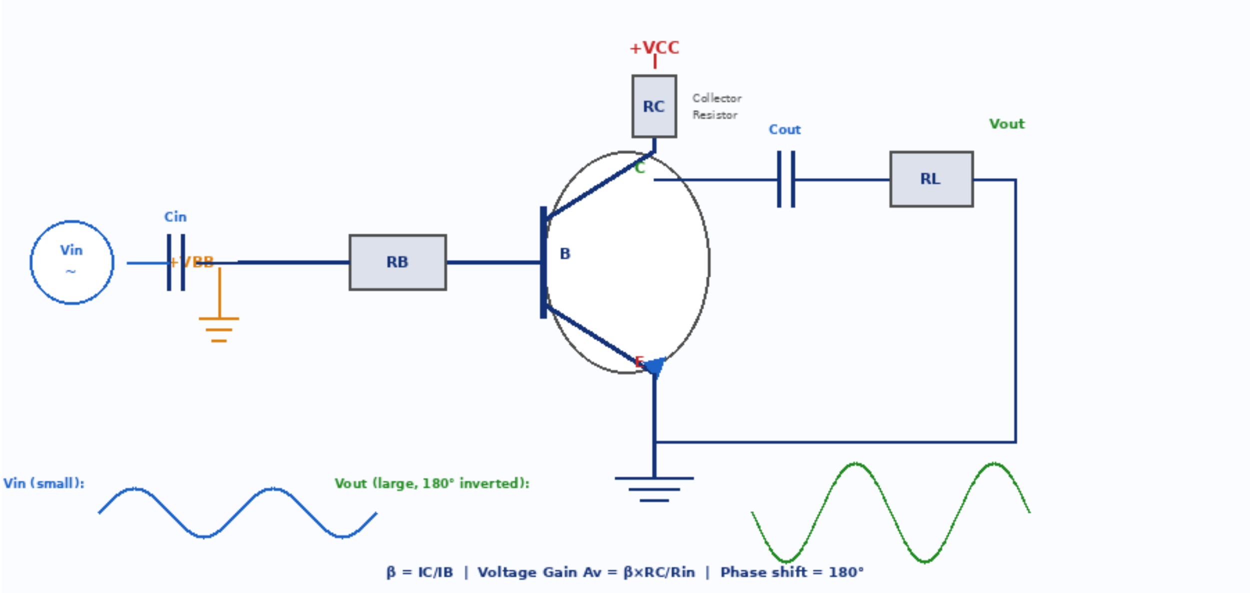

Fig 9: NPN Transistor CE Amplifier – Shows RB, RC, VBB, VCC, coupling capacitors Cin & Cout, small input waveform and large phase-inverted output waveform

9. Photocell (Photoelectric Cell)

9.1 Working Principle

A photocell is a device that converts light energy into electrical energy (or changes its electrical resistance) based on the photoelectric effect. When light of sufficient frequency falls on the photosensitive surface (cathode), electrons are emitted due to the photoelectric effect. These electrons are collected by the anode, causing a current to flow in the external circuit. The amount of current depends on the intensity of light incident on the cathode.

- Based on the External Photoelectric Effect
- Consists of: Evacuated or gas-filled glass tube, Photosensitive cathode (coated with alkali metals like Cs, Na), Metallic anode
- Photocurrent is proportional to the intensity of incident light
- Photocurrent is independent of the frequency of light (as long as frequency > threshold frequency)
- No current flows if frequency of light < threshold frequency (nu < nu0)
- **Einstein's Photoelectric Equation:** `KE_max = h*nu - W  (W = work function)`

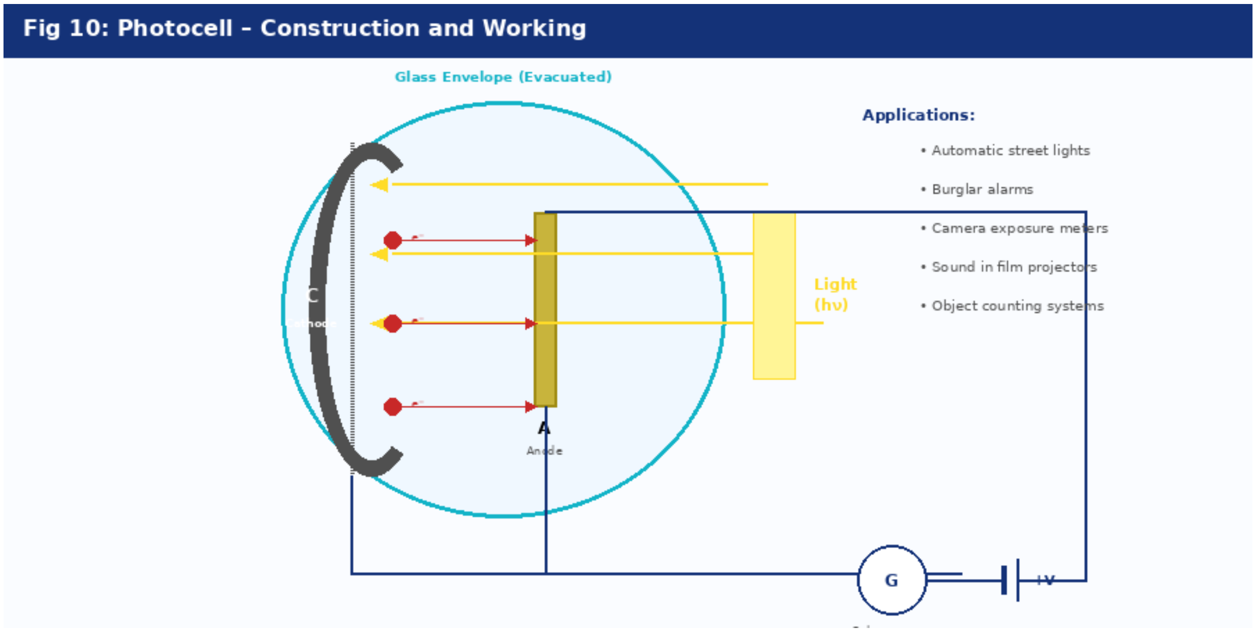

Fig 10: Photocell – Glass envelope with curved photosensitive cathode (C), rod anode (A), light rays causing electron emission, external galvanometer circuit

9.2 Applications

- Automatic street light control (switch on at dusk, off at dawn)
- Burglar alarm systems (light beam interruption triggers alarm)
- Counting systems on production lines (objects interrupt beam)
- Exposure meters in cameras
- Fire and smoke detectors
- Opening of automatic doors in buildings
- Sound reproduction in motion picture projectors (optical soundtracks)

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10. Solar Cell (Photovoltaic Cell)

10.1 Working Principle

A solar cell is a p-n junction device that directly converts sunlight (solar energy) into electrical energy using the photovoltaic effect. When photons from sunlight strike the p-n junction, they impart energy to electrons in the valence band, creating electron-hole pairs near the junction. The built-in electric field of the depletion region separates these pairs — electrons move toward the n-side and holes move toward the p-side. This generates a potential difference (voltage) across the terminals, which can drive current through an external load.

- Based on Photovoltaic Effect — light creates a voltage across a p-n junction
- No external battery required — solar cell itself is the source of EMF
- Made from: Silicon (most common), GaAs, CdTe, organic materials
- Top surface (light-receiving side): n-type Si (thin, transparent)
- Bottom surface: p-type Si (thick base)
- **Open Circuit Voltage (Voc):** `Typically 0.5 to 0.6 V per cell for Silicon`
- **Short Circuit Current (Isc):** `Proportional to light intensity and cell area`
- **Efficiency:** `Commercial Si cells: 15-22%, Lab cells: up to 45%`

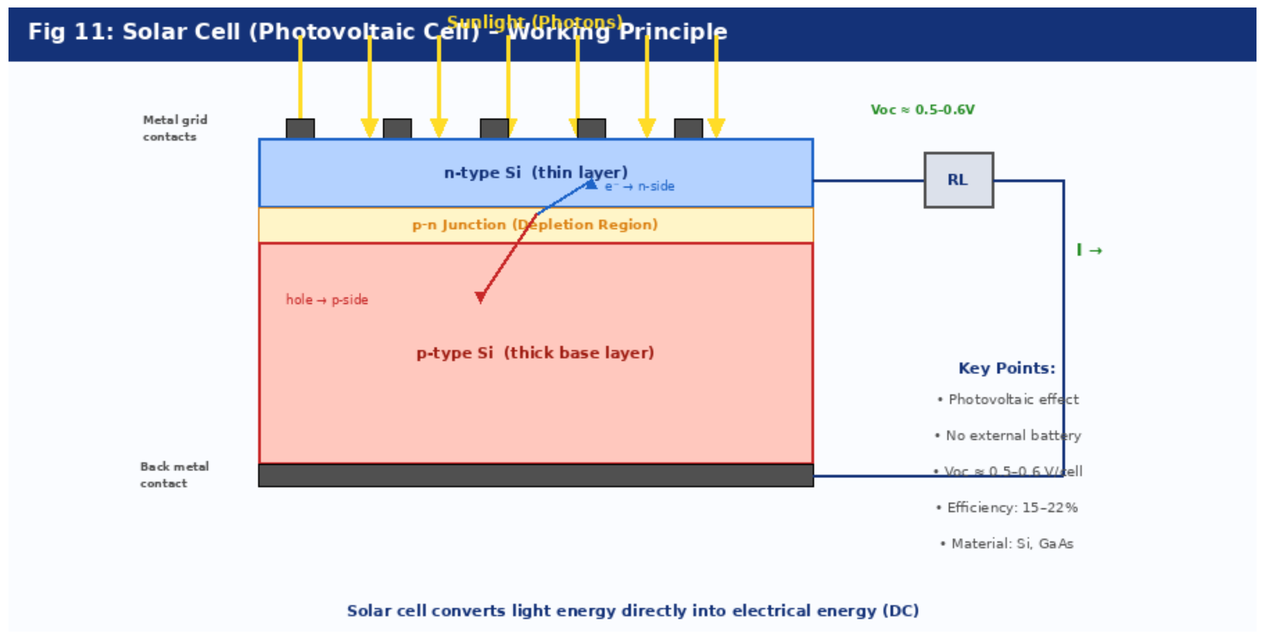

Fig 11: Solar Cell – Sunlight hitting n-type top layer, electron-hole pair generation at junction, charge separation by built-in field, DC current through external load RL

10.2 Engineering Applications

- Solar power plants for electricity generation (grid-scale)
- Rooftop solar panels for homes and buildings (on-grid and off-grid)
- Powering satellites and space stations
- Solar-powered street lights, water pumps, calculators
- Remote area power supply where grid electricity is unavailable
- Electric vehicles charging using solar energy
- Portable solar chargers for mobile devices

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11. LED (Light Emitting Diode)

11.1 Working Principle

A Light Emitting Diode (LED) is a p-n junction device that emits light when forward biased. When a forward voltage is applied, electrons from the n-side and holes from the p-side are injected across the junction. When these electrons recombine with holes, they release energy in the form of photons (light). This phenomenon is called electroluminescence. The color (wavelength) of the emitted light depends on the band gap of the semiconductor material used.

- Based on the principle of Electroluminescence
- Must be forward biased to emit light

- No filament — does not produce heat light like incandescent bulbs
- Semiconductor materials and corresponding colors:
  - GaAsP (Gallium Arsenide Phosphide) — Red light
  - GaP (Gallium Phosphide) — Green or Yellow light
  - GaN (Gallium Nitride) — Blue light
  - InGaN — White light (used in white LED lamps)
- **Photon Energy:** `E = h*nu = Eg  (energy of emitted photon = band gap energy)`
- **Wavelength of emitted light:** `lambda = hc / Eg`
- Forward voltage for LEDs: 1.5 V to 3.5 V depending on color
- Always connect a series resistor to limit current and prevent damage

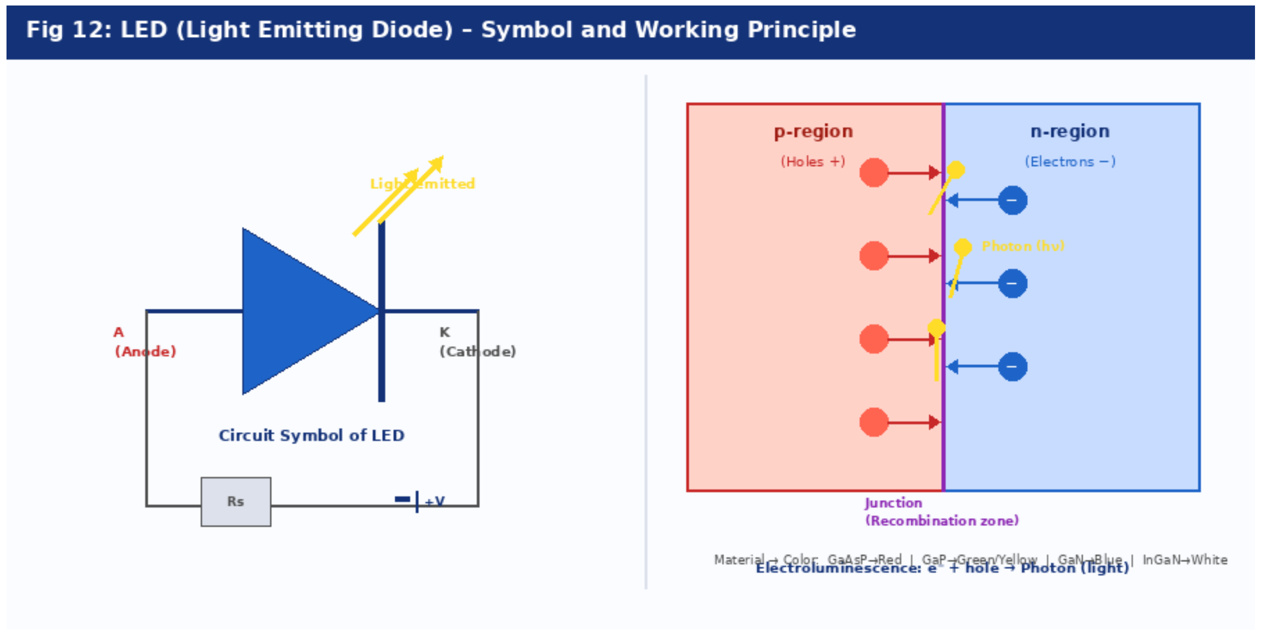

Fig 12: LED – Circuit symbol (diode with light arrows), p-n junction showing electron-hole recombination producing photons (electroluminescence), material-to-color table

11.2 Advantages and Applications

LEDs are highly efficient, long-lasting, and compact light sources that have revolutionized lighting and display technology. Their advantages include very low power consumption, long lifespan (up to 50,000 hours), no warm-up time, and ability to emit colored light directly without filters.

- Indicator lamps in electronic equipment and panels
- Seven-segment displays for calculators, clocks, meters
- Traffic signals and railway signals
- LED street lights and room lighting
- Backlighting for LCD screens (TVs, monitors, mobile phones)
- Remote controls (Infrared LEDs)
- Optical fiber communication (as light source)
- Vehicle headlights and tail lights

KEY FORMULAS SUMMARY

Quantity	Formula	Typical Values
Band Gap (Si)	`Eg = 1.1 eV`	1.1 eV
Band Gap (Ge)	`Eg = 0.67 eV`	0.67 eV
Diode Equation	`I = Io*(e^V/VT - 1)`	Io ~ nA
HWR Output Voltage	`Vdc = Vm / pi`	~0.318 Vm
FWR Output Voltage	`Vdc = 2Vm / pi`	~0.636 Vm
HWR Ripple Factor	`r = 1.21`	High ripple
FWR Ripple Factor	`r = 0.48`	Better quality
Transistor Gain	`beta = IC / IB`	50 to 300
Collector Current	`IC = beta * IB`	mA range
Photon Energy (LED)	`E = hc / lambda`	1.5 – 3.5 eV
HWR Efficiency	`eta = 40.6%`	Low
FWR Efficiency	`eta = 81.2%`	Better

IMPORTANT FOR EXAM

1. Difference between conductor, semiconductor, and insulator (with band gap values)
2. Intrinsic vs Extrinsic semiconductor — definition, carriers, examples
3. Formation of p-n junction and depletion region concept
4. Forward and reverse bias — behavior and applications
5. V-I characteristics of p-n junction diode
6. Half wave rectifier — circuit, working, waveform, Vdc formula
7. Full wave rectifier (centre tap) — circuit, working, waveform, comparison with HWR
8. NPN vs PNP transistor — structure, symbol, carriers
9. Transistor as amplifier in CE mode — circuit, current gain (beta)
10. LED working principle and material-to-color relationship
11. Solar cell — photovoltaic effect and working
12. Photocell working principle and applications

COMMON VIVA QUESTIONS

Q1: What is a semiconductor? Give two examples.

Q2: Why does conductivity of a semiconductor increase with temperature?

Q3: What is the difference between n-type and p-type semiconductor?

Q4: What is a depletion region in a p-n junction?

Q5: What is the cut-in voltage of a silicon diode?

Q6: What is the difference between half wave and full wave rectifier?

Q7: What is ripple factor? Which rectifier has lower ripple?

Q8: What is the function of a transistor?

Q9: In CE mode amplifier, is there a phase difference between input and output?

Q10: What is the principle of LED? Why does it emit colored light?

Q11: What is the photovoltaic effect? Name one application.

Q12: What is the difference between a solar cell and a photocell?

Q13: What is the current gain (beta) of a transistor?

Q14: Why is the base of a transistor made very thin?

Q15: What is the frequency of ripple in a full wave rectifier connected to 50 Hz supply?

End of Unit 6 — Semiconductor Physics

Applied Physics | 2nd Semester | Diploma/Polytechnic Engineering