UNIT IV - SOLAR PHOTOVOLTAICS

Fundamentals of solar cells- - types of solar cell- P-N junction photodiode- description and principle of working of a solar cell- cell structure- solar module and panel- I-V characteristics of a PV module- maximum power point- cell efficiency- fill factor- Manufacturing of solar cell - Case study on Evaluation of Solar Photovoltaics

1. Fundamentals of Solar Cells

A solar cell converts **sunlight directly into electricity** using the **photovoltaic effect**. When photons hit a semiconductor (typically silicon), they excite electrons, generating **electron-hole pairs**. These are separated by an internal electric field at a **p-n junction**, producing **direct current (DC)** electricity.

Real-time scenario: Solar-powered calculators, garden lamps, and mobile phone chargers use this principle on a small scale.

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2. Types of Solar Cells

Type	Material	Efficiency	Application
Monocrystalline Silicon	Single-crystal silicon	18–22%	Rooftop solar panels, high-end solar plants
Polycrystalline Silicon	Multi-crystal silicon	15–18%	Residential rooftops, schools
Thin-Film (CdTe, CIGS)	Flexible materials	10–13%	BIPV, Solar backpacks, building facades
Perovskite/Organic (R&D)	Hybrid/organic compounds	15–25% (lab)	Under research; flexible solar applications

Scenario: Tata Power Solar and Vikram Solar in India manufacture both mono and polycrystalline panels for residential and industrial deployment.

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3. P-N Junction Photodiode

The **p-n junction** forms the heart of a solar cell.

- The **p-side** has holes; the **n-side** has free electrons.
- When exposed to sunlight, an electric field at the junction separates the photo-generated electron-hole pairs, generating usable current.

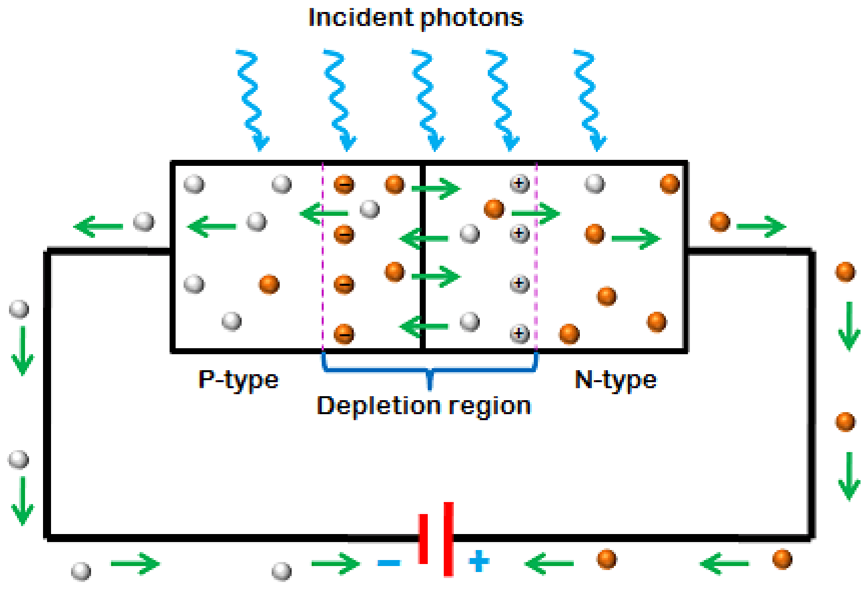
Principle

The P-N junction photodiode works on the principle of the **photovoltaic effect** or **photoelectric effect**. When **incident photons** (light energy) strike the **depletion region** of a p-n junction, they generate **electron-hole pairs**. These charge carriers are then separated by the built-in electric field, resulting in a **flow of current** in the external circuit.

Construction

As shown in the diagram, the P-N junction photodiode consists of:

- **P-type Semiconductor:** Contains an excess of holes (positively charged carriers).
- **N-type Semiconductor:** Contains an excess of free electrons (negatively charged carriers).
- **Depletion Region:** The interface between p-type and n-type, where the electric field exists.
- **External Circuit:** A closed loop allowing current to flow when electron-hole pairs are separated.
- **Photon Source (light):** Incident on the depletion region to generate carriers.



PN Junction photodiode

Note from Diagram:

- Blue zig-zag lines = incident photons
- Brown = electrons, White = holes
- Green arrows = direction of current flow

Working (Based on Diagram)

1. **Photons** from sunlight (or any light source) hit the **depletion region**.
2. **Electron-hole pairs** are generated by the energy of photons.
3. The **internal electric field** in the depletion region:
   - Drives electrons toward the **n-side**
   - Drives holes toward the **p-side**
4. These charges flow through the **external circuit**, producing a **photo-current**.
5. The process continues as long as photons are incident.

In summary: Light energy → charge generation → separation → current flow.

Advantages

Converts light directly into electricity (no moving parts)

High-speed response time

Simple, compact, and durable

Works well in low-light conditions

Disadvantages

Sensitive to temperature changes

Limited power output (needs many cells for usable voltage)

Degradation over time under high UV

Needs precise fabrication techniques

Applications

Application Area	**Example Use**
Solar Cells	Photovoltaic panels for energy generation
Light Sensors	Streetlights, solar garden lamps
Optical Communication	Fiber optic receivers
Safety Devices	Smoke detectors, flame sensors

Application Area	Example Use
Consumer Electronics	Solar calculators, watches, remotes

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4. Description & Principle of Solar Cell Operation

1. Sunlight hits the solar cell and excites electrons.
2. Electron-hole pairs are generated in the depletion region.
3. Electric field pushes electrons toward the n-side and holes to the p-side.
4. Flow of charges through external circuit = **DC electricity**.

Scenario: Solar lanterns used in rural India are based on this simple principle.

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5. Cell Structure

Basic solar cell structure includes:

- Transparent cover (glass)
- Anti-reflective coating
- N-type and P-type silicon layers
- Metal contacts (top and bottom)
- Backsheet

Tip: Use a labeled diagram in exams — commonly asked!

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6. Solar Module & Panel

- One **solar cell** gives ~0.5 V
- **Cells in series** → Module (~18–40 V)
- **Modules in series/parallel** → Solar panel or array (for real applications)

Scenario: A 5 kW rooftop system (~14 panels) powers an entire 3BHK home, running lights, fans, TV, and refrigerator.

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7. I-V Characteristics of PV Module

The **I-V curve** shows how current varies with voltage at a given irradiance.

Key Points on Curve:

- **Short Circuit Current (Isc):** Max current at V = 0
- **Open Circuit Voltage (Voc):** Max voltage at I = 0
- **Maximum Power Point (Vm, Im):** Optimal operating point

Graph Sketch:

Y-axis: Current (I)

X-axis: Voltage (V)

Plot curve bending down with MPP near the knee

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8. Maximum Power Point (MPP)

Defined as the point where:

$$P_{max} = V_m \times I_m$$

Modern solar inverters use **MPPT (Maximum Power Point Tracking)** to constantly adjust voltage and current for max efficiency.

Real-time Example: Solar water pumps in agriculture use MPPT to ensure maximum water flow during sunny hours.

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9. Cell Efficiency

$$\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{V_{oc} \cdot I_{sc} \cdot FF}{P_{in}} \times 100$$

- Typical efficiencies:
    - Monocrystalline: 20%
    - Polycrystalline: 16%
    - Thin-film: 12%

Scenario: Higher-efficiency panels require less roof space - ideal for urban homes with space constraints.

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10. Fill Factor (FF)

$$FF = \frac{V_m \cdot I_m}{V_{oc} \cdot I_{sc}}$$

A measure of quality - FF close to **0.75 - 0.85** means better-performing cells.

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11. Manufacturing of Solar Cells

Steps:

1. Silicon purification
2. Crystal growth (Czochralski process)
3. Wafer slicing
4. Doping (p-n junction formation)
5. Anti-reflective coating
6. Contact printing
7. Cell testing
8. Module assembly (lamination + glass)

India's solar cell manufacturing hubs: Gujarat, Telangana, and Tamil Nadu (e.g., Adani Solar, Waaree Energies)

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12. Case Study – Rooftop PV Evaluation (Real Scenario)

Project: 100 kW rooftop solar installation

Location: Coimbatore Engineering Campus

Specs:

- 330 W monocrystalline panels
- 303 panels total
- Grid-tied with net metering
- MPPT inverters
- Output: ~145,000 kWh/year
- Payback: ~4.5 years
- CO_2 offset: ~130 tons/year

Impact: Reduced annual energy bills by 60%, served as a live renewable energy lab for students.

Summary Table

Concept	Key Point
Photovoltaic Effect	Converts light to electricity in semiconductors
Types of Cells	Mono, Poly, Thin-film, Perovskite
I-V Curve	Identifies max power point
Efficiency	% of sunlight converted to electricity
Fill Factor	Indicates quality of cell performance
MPPT	Ensures max power extraction from module
Real Application	Rooftop power, rural solar pumps, solar lights

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Bonus: Real-Time Applications of Solar PV

- **Solar water pumps** – replacing diesel pumps in Indian farms
- **Off-grid lighting systems** – in villages without electricity
- **Solar EV charging stations** – in smart cities
- **Building-Integrated Photovoltaics (BIPV)** – glass facades with solar function
- **Wearables** – solar-powered backpacks, watches, calculators

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End Semester Questions

PART A (2 Marks Questions)

1. Illustrate the need for doping in solar cells. efficiency **(April / May 2022)**
2. Summarize the factors that contribute to solar cell efficiency **(April / May 2022)**
3. Distinguish the difference between PV and other solar energy technologies. **(April / May 2023)**
4. Define Infer fill factor. **(April / May 2023)**
5. Compare a solar module and a panel. **(April / May 2024)**
6. How are solar cells manufactured? **(April / May 2024)**

PART B

1. Interpret the construction and working of a PV cell with a neat sketch by its application in real time. **(April / May 2022)**
2. (i) Analyze the I-V characteristics of a PV cell along with neat sketches. (ii) Identify the types of solar cells with their applications **(April / May 2022)**
3. (i) Illustrate the I-V characteristics of a PV cell along with neat sketches. (8 Marks) (ii) Infer the process of manufacturing solar cells with a neat sketch. (8 Marks) **(April / May 2023)**
4. Contrast the need and working of solar Photovoltaic cells with relevant sketches with case study. **(April / May 2023)**
5. What is meant by a solar cell? Explain the working principle of a solar cell with a neat sketch. **(April / May 2024)**
6. Interpret the construction and working principle operation of a solar photovoltaic system. **(April / May 2024)**