REVA UNIVERSITY

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SUSTAINABLE SOLAR ENERGY TECHNOLOGIES

Department of Chemistry, School of Applied sciences

OPEN ELECTIVE

SUSTAINABLE SOLAR ENERGY TECHNOLOGIES

SYLLABUS

COURSE CODE: B24ASO603

CREDIT : 3

Semiconductor materials and device technologies: Semiconductors, Band structures - energy scales, quantum aspects, band gap modulation, Silicon single crystal, Different semiconductors, p-n junction, various heterojunctions, MOS, molecular and polymeric semiconducting materials, advanced transparent conducting substrates, solar concentrators, semiconductors, quantum dots importance of semiconductors in device technologies, Effects of size reduction – thin film device technologies.

Case studies: Semiconductor processing - Industrial processes and challenges, Solar grade semiconductors preparation.

COURSE OUTCOMES

	Course Outcomes	POs	PSOs
CO1	Evaluate the intricate problems in solar energy conversion and solution through clean energy systems.	1,2,12	1,2,3
CO2	Value the advances in different solar energy conversion processes.	1,2,	1,2,3
CO3	Perceive the need of solar energy conversion materials in semiconductor devices technologies.	1,2	1,2,3
C04	Judge and implement different semiconductor in photoelectrosynthesis.	1,2,12	1,2,3
C05	Critically analyze the cost and implementation of solar technologies – solar to electric, solar to chemical, solar to thermal, solar to light.	1,2	1,2,3
C06	Analyze the importance of miniaturization of devices and nanotechnology.	1,2,12	1,2,3

INTRODUCTION TO SEMICONDUCTORS

Semiconductors are materials with electrical properties intermediate between conductors and insulators. Their conductivity can be controlled by **doping, temperature, or external fields,** making them essential for modern electronic devices such as **transistors, diodes, and integrated circuits.**

The electronic properties of semiconductors are explained using **band theory.**

Energy Bands: In solids, atomic orbital's overlap, forming continuous energy bands.

1. **Valence Band (VB)**: Filled with electrons at absolute zero temperature.
2. **Conduction Band (CB)**: Empty at absolute zero but can be occupied when electrons gain energy.
3. **Band Gap (Eg)**: The energy difference between the conduction band and valence band. It determines electrical conductivity.

Materials can be divided into 3 types based on the values of energy gap

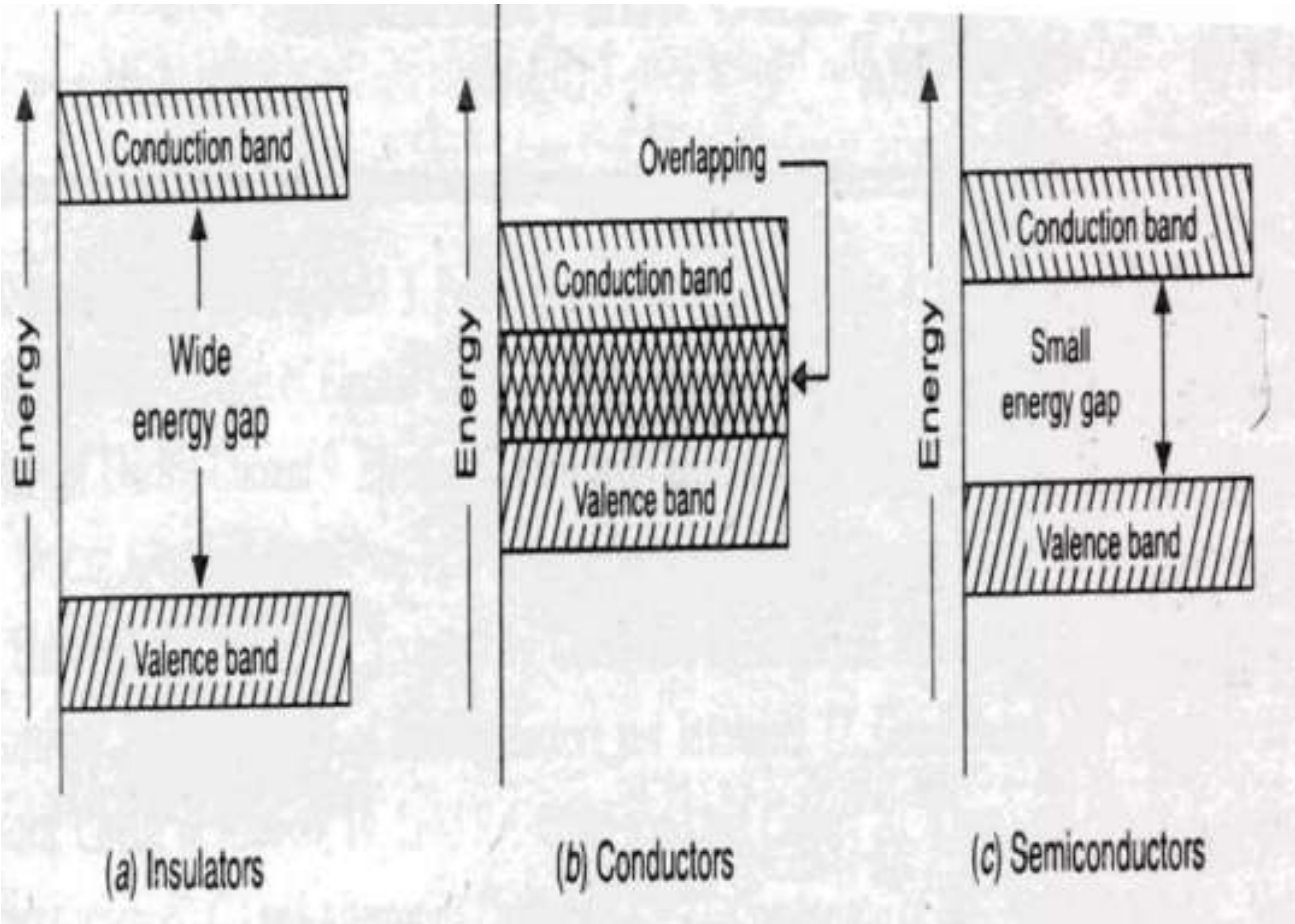
❖ ≈ 0 eV)

❖ **Semiconductors**: Small band gap (Eg ≈ 0.1 - 4 eV)

❖ **Insulators**: Large band gap (Eg > 5 eV)

- **Silicon (Si):** Band gap ≈ 1.12 eV (indirect band gap)
- **Germanium (Ge):** Band gap ≈ 0.66 eV
- **Gallium Arsenide (GaAs):** Band gap ≈ 1.43 eV (direct band gap)

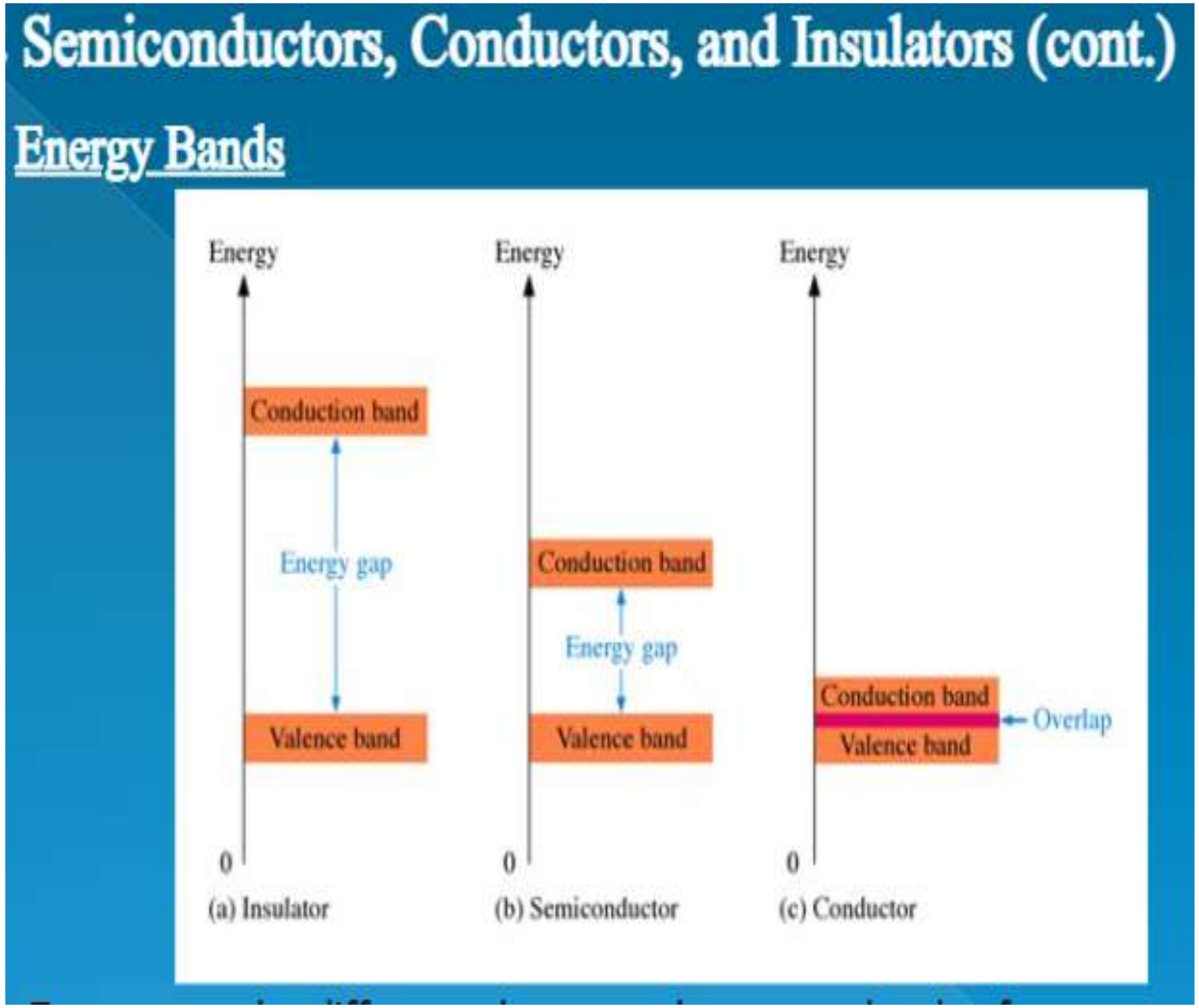
TYPES OF MATERIALS



- Ex: glass, Diamond, Silicon di oxide
- Energy gap of diamond is ~6ev.

- Ex: All metals.
- Best conducting materials are
  - Silver is best, cupper is second best

- Ex: Si, Ge

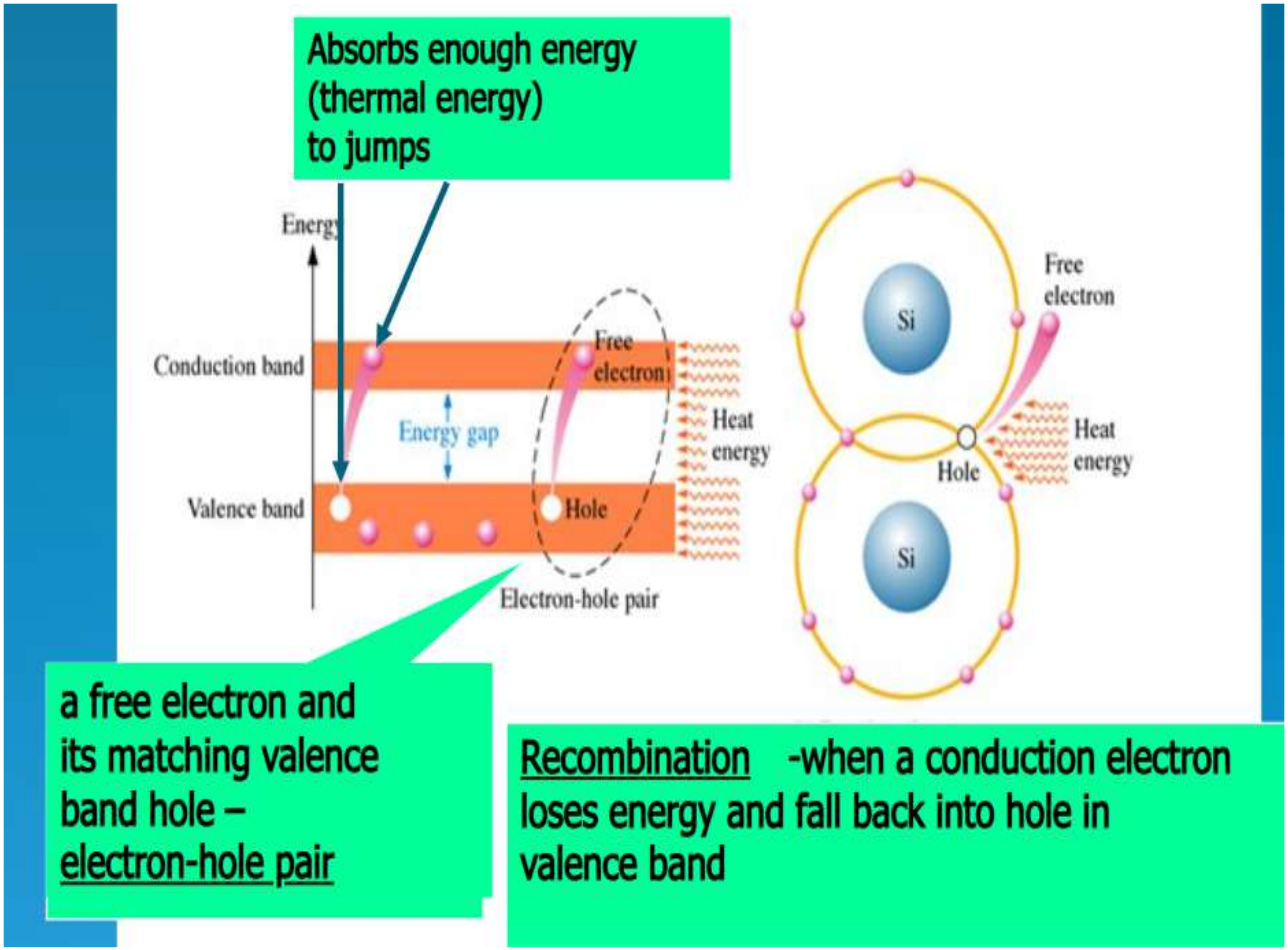


- Energy gap-the difference between the energy levels of any two orbital shells

- Band-another name for an orbital shell (valence shell=valence band)

- Conduction band - the band outside the valence shell where it has free electrons.

Semiconductor processes



SEMICONDCUTOR

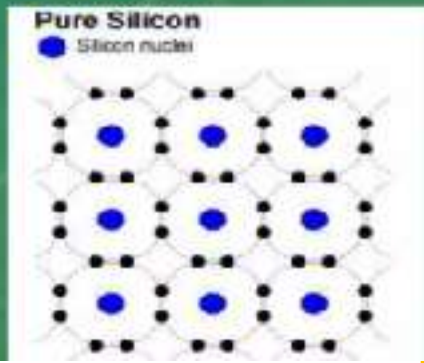
- The materials, in which the conduction and valence bands are separated by a **small energy gap (1eV)** are called semiconductors.
- **Silicon and germanium** are the commonly used semiconductors.
- A small energy gap means that a small amount of energy is required to free the electrons by moving them from the valence band in to the conduction band.
- The **semiconductors behave like insulators at 0K,** because no electrons are available in the conduction band.
- **If the temperature is further increased,** more valence electrons will acquire energy to jump into the conduction band.
- If a valence electrons receives sufficient thermal energy, it can move into conduction band leaving a vacancy in valence band, which is called hole and therefore, if one e- is sufficiently thermally energized it creates a pair of free e- and hole, this process is called **carrier generation.**

SEMICONDCUTOR

- Carrier generation can happen due to
- Thermal excitation
- Photo excitation
- Electrical excitation
- Impact ionization

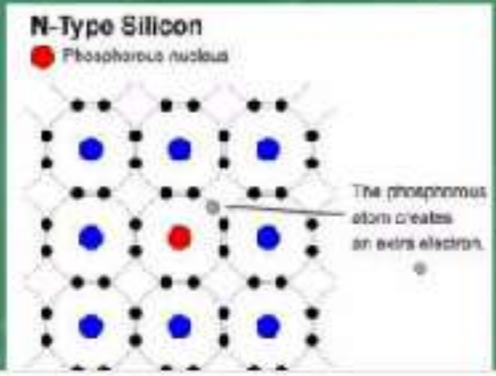
Intrinsic SC

- IV group is carbon, Si, Ge, Tin, Lead.
- In it sc crystal each atom forms four covalent bonds to become stable.
- At 0^0 , all valence e- participate in covalent band formation. Conduction not possible.
- if temp is increases, greater no of free e- hole pair will be created. Causes conduction
- $n=p=n_i$
- $J=n_i(u_n+u_p)eE$



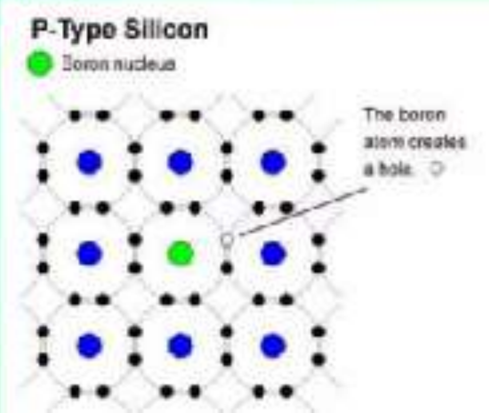
N type SC

- V^{th} group Phospurs, Arsenic, Antimon.
- P forms 4 covalent bonds with Si and donate 5^{th} electron to crystal. It is called free e-.
- According to law of Nutrality $n_n=p_n+n_D$
- Mass action law $n_n.p_n=n_i^2$
- Majority is e-
  minority is holes



P type SC

- 3^{rd} group B, Al, Ga.
- B forms 3 covalent bonds with Si and forms 4^{th} bond with hole formation.
- According to law of Nutrality $n_p+n_A=p_p$
- Mass action law $n_p.p_p=n_i^2$
- Majority is holes
  minority is e-



BAND GAP MODULATION IN SEMICONDCTORS

Band gap engineering allows tuning of semiconductor properties for applications such as lasers, LEDs, and transistors.

1. **Alloying**: Mixing materials like GaAs and AlAs to create GaAlAs with a different band gap.

2. **Strain Engineering**: Applying mechanical stress to alter the electronic band structure.

3. **Quantum Well :** Thin-layered semiconductor structures modify quantum confinement effects, leading to altered band gaps. In quantum dots, nanowires, or thin films, reducing the size of the material to the nanoscale increases the band gap due to confinement of charge carriers.

   Example: CdSe quantum dots exhibit size-dependent fluorescence (color tuning in displays and bio-imaging).

4. **Doping and External Fields:** Introducing impurities (donors or acceptors) to shift the Fermi level and control conductivity.

   Applying **electric fields (Stark effect)** or **magnetic fields (Zeeman effect)** can modify band structures.

5. Phase Transition and Temperature Dependence

- Some materials exhibit band gap change due to phase transitions.
- Temperature variations can also shift the band gap due to thermal expansion.
- Example: VO_2 undergoes an insulator-to-metal transition around 68°C, useful in smart windows.

6. Heterostructures and Superlattices

- Engineering layered structures with alternating materials (e.g.,GaAs/AlGaAs quantum wells) modifies carrier confinement and band alignment.
- Used in high-speed transistors and optoelectronic devices.

Essentials in semiconductor technology

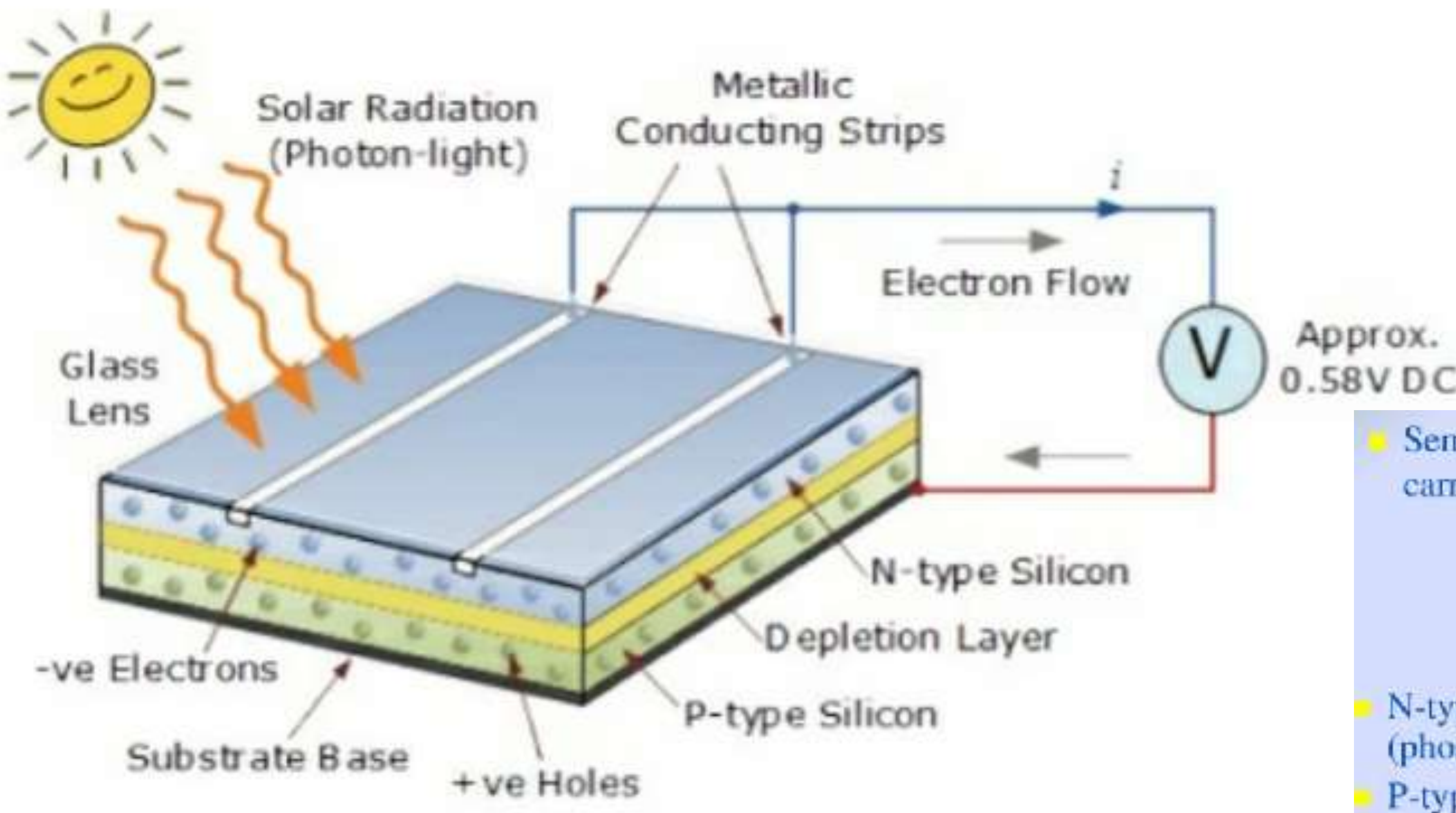
- Need of semiconductor **with band gap within 3 eV to 1 eV** to balance efficient light absorption and electron excitation.
- **Broad absorption in visible spectral region** - Semiconductors should have broad absorption in the visible spectrum for applications in photonic and optoelectronic devices.
- Photoactive materials should be **direct band gap semiconductor** because they enable effective absorption with thinner films, minimizing recombination rates. Materials like gallium arsenide (GaAs) highly efficient at absorbing and emitting light, which is ideal for applications such as LEDs, laser diodes, and photovoltaic cells.
- As **indirect bandgap semiconductor require higher thickness** of thin film for good absorption. However higher thickness always result in higher recombination rates and reduce efficiency. Materials such as silicon have lower light absorption efficiencies and need thicker material layers to absorb light effectively. However, they are often used in electronic applications like transistors and integrated circuits, where light absorption is not the primary concern.

Semiconductor technology

- Semiconductor applications, includes,
- Electronic components such as diodes, triodes, transistors, FETs, ferroelectric transistors.
- **Semiconductors are foundational for LEDs**, photo detectors, lasers, and amplifiers, sensing technologies, Integrated circuits.
- **Memory and computing devices** (like DRAM, SRAM, and flash) have improved storage capacity, speed, and energy efficiency for computers and mobile devices, and integrated circuits.
- **High-Speed Microchips**: Advanced microchips now perform hundreds of millions of calculations in fractions of a second, supporting intensive data processing in various applications.
- **Photo conversion Technologies**: Semiconductors are essential in solar cells and other devices that convert light into electricity, helping advance renewable energy technologies.

Solar Cell Construction

Solar cell it is a solid state electrical device that converts energy of light directly into electricity by **Photoelectric Effect**.



- Semiconductor material can be p-type (hole carriers) or n-type (electron carriers)

- N-type has impurities with an extra electron (phosphorus)
- P-type has impurities with one fewer electron (boron)
- Put them together: p-n junction
- A solar cell is a very large p-n junction (or diode)

- Mainly Solar cell is constructed using the crystalline Silicon that consists of a n-type semiconductor. This is the first or upper layer also known as emitter layer.
- The second layer is p-type semiconductor layer known as base layer.
- Both the layers are sandwiched and hence there is formation of p-n junction between them.
- The surface is coated with anti-reflection coating to avoid the loss of incident light energy due to reflection.

P-N JUNCTION

A **p-n junction** is the core of a photovoltaic cell. It is formed by joining two types of semiconductor material.

1. **P-type Semiconductor:** Doping with an element like **boron** (has 3 valence electrons) creates holes (missing electrons) in the semiconductor, **making it positively charged.**

2. **N-type Semiconductor:** Doping with an element like **phosphorus (**has 5 valence electrons) adds extra free electrons**, making it negatively charged.**

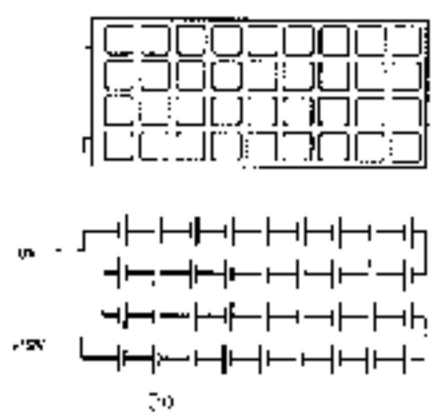
Formation the p-n Junction

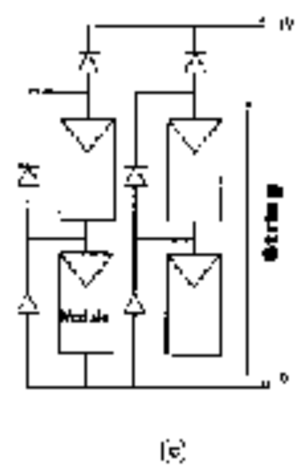
When p-type and n-type semiconductors are brought together. Electrons from the N-type region move into the P-type region, where they recombine with holes. This movement creates a depletion region near the junction, where there are no free charge carriers. The recombination of electrons and holes near the junction results in an **electric field.** This electric field acts as a diode, allowing current to flow in only one direction (from P to N), preventing charge carriers from recombining freely.

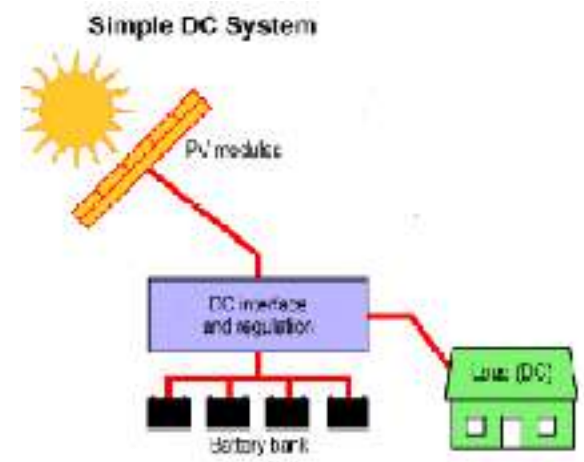
PHOTOVOLTAIC CELLS, MODULES AND SYSTEMS

- Solar cell is the basic building blocks of solar PV.
- Cells are connected together in series and encapsulated into models.
- Modules can be used singly, or connected in parallel and series into an array with a larger current & voltage output.
- PV arrays integrated in systems with components for charge regulation and storage.


Cell


module


array



system

SILICON SINGLE CRYSTAL

A **silicon single crystal** is a highly ordered form of silicon in which the entire structure consists of a continuous and unbroken lattice with no grain boundaries.

Monocrystalline cell

Properties

High Purity: Typically 99.9999% (6N) or higher.

Excellent Electrical Properties: Used in electronic devices due to controlled doping.

Thermal Conductivity: Good heat dissipation in electronic applications.

Optical Properties: Used in infrared optics due to its transparency in IR wavelengths.

PRODUCTION METHOD OF SINGLE CRYSTAL Si

a) Czochralski (CZ) Method

The CZ method is the most common technique for producing large silicon single crystals.

Process Steps:

- A small silicon seed crystal is dipped into molten silicon (~1420°C).
- The seed is slowly pulled and rotated, allowing the molten silicon to solidify in a crystalline structure.
- The result is a cylindrical single crystal (ingot), which is then sliced into wafers.

b) Float-Zone (FZ) Method

- This technique produces high-purity silicon crystals by melting and recrystallizing a silicon rod.

Process Steps:

- A high-purity silicon rod is placed in a vertical position.
- A radiofrequency (RF) heating coil moves along the rod, melting and recrystallizing it.
- The impurities move toward the molten zone, leaving behind ultra-pure silicon.

APPLICATIONS OF SILICON SINGLE CRYSTALS

a) **Semiconductor Industry**

- Microprocessors & Transistors: Used in nearly all modern electronic devices.
- Integrated Circuits (ICs): Found in smart phones, computers, and IoT devices.

b) Photovoltaics (Solar Cells)

- Monocrystalline silicon solar cells offer higher efficiency (~20-25%) compared to polycrystalline silicon.
- Used in residential, commercial, and space applications.

c) Power Electronics

- High-voltage applications such as electric vehicle inverters, power grids, and industrial automation.
- Silicon-based MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) and IGBTs (Insulated-Gate Bipolar Transistors) are widely used.

d) Infrared Optics

- Silicon single crystals are used in IR lenses, night vision systems, and thermal imaging cameras.

e) MEMS (Micro-Electro-Mechanical Systems)

- Used in accelerometers, gyroscopes, pressure sensors, and biomedical devices.

DIFFERENT SEMICONDUCTORS

1. PV cells are primarily composed of semiconductor materials that have a higher conductivity than insulators. However, these materials are not good conductors of electricity like metals. Different types of semiconductors, such as crystalline silicon (c-Si) and cadmium telluride (CdTe), are used in solar cells.

2. Semiconductors in PV cells absorb the light's energy when they are exposed to it and transfer the energy to electrons. The absorbed additional energy allows electrons to flow in form of an electrical current through the semiconductor material.

3. Subsequently, **conductive metal contacts/grid**-like lines on solar cells collect the current generated in the semiconductor. Solar cells are connected to form larger power-generating units known as solar panels.

COMMONLY USED SEMICONDUCTOR MATERIALS IN SOLAR CELLS

- **Silicon** is a common material for PV cells because it's abundant and effective at converting light to electricity. In crystalline silicon (c-Si) cells, silicon atoms are arranged in a crystal structure, boosting efficiency to 18%-22% in industrially-made modules. These silicon cells can last 25 years, maintaining 80% of their original power.

- **Copper indium gallium diselenide** (CIGS) and **cadmium telluride (**CdTe) are also used in thin-film solar cells. CdTe cells are cheaper to make but are less efficient than silicon cells.

- CIGS cells possess high efficiencies and suitable properties as PV semiconductor materials. However, the **manufacturing of these materials** by combining four elements is extremely **challenging.** Moreover, both CIGS and CdTe require greater protection than silicon to ensure long-lasting operations.

- **Perovskite semiconductors** can be assembled easily and realize efficiencies similar to c-Si. However, perovskite cells have a shorter lifetime than c-Si cells.
- **Organic semiconductors** in solar cells can be tailored for features like transparency or bandgap. Organic PVs are cheaper to produce on a large scale, but they are less efficient and have shorter lifespans than c-Si cells.
- **Quantum dot solar cells** uses nano sized semiconductor particles to conduct electricity, and their bandgap can be adjusted to absorb hard-to-capture light. They can also be combined with other materials like perovskites to boost performance. However, quantum dots aren't very efficient at converting light into electricity.

VARIOUS HETEROJUNCTIONS IN SEMICONDUCTORS

A **heterojunction** is a junction formed between two different semiconductor materials with different bandgaps, electron affinities, or lattice constants. Heterojunctions offer enhanced performance in various electronic and optoelectronic applications.

Homojunction - which is formed between two identical semiconductors, like p-n junctions in silicon.

Types of Heterojunctions

Heterojunctions can be classified based on **band alignment**, **carrier transport**, and **material composition**.

Band alignment describes **how the conduction band (CB) and valence band (VB) of two different semiconductor materials align when they form a heterojunction.** This alignment determines how electrons and holes move across the junction, impacting the performance of devices like transistors, LEDs, solar cells, and photodetectors.

Alignment Type	Conduction Band Offset (ΔE_C)	Valence Band Offset (ΔE_V)
Type-I (Straddling Gap)	CB of material 2 is lower than CB of material 1	VB of material 2 is higher than VB of material 1
Type-II (Staggered Gap)	CB and VB are both shifted	**Electrons & holes reside in different materials**
Type-III (Broken Gap)	CB of material 2 is **below** the VB of material 1	No bandgap overlap

Material 1	Material 2	Bandgap (eV)	Type of Alignment	Application
GaAs	**AlGaAs**	1.42 / 1.9	**Type-I**	Lasers, LEDs, quantum wells
GaN	**AlGaN**	3.4 / 4.1	**Type-I**	High-power HEMTs, UV LEDs
Si	**SiC**	1.12 / 3.26	**Type-I**	High-power electronics
GaSb	**InAs**	0.73 / 0.36	**Type-II**	Infrared photodetectors
CdTe	**CdS**	1.45 / 2.42	**Type-II**	Solar cells
InAs	**GaSb**	0.36 / 0.73	**Type-III**	Tunnel FETs, infrared sensors

BASED ON CARRIER TRANSPORT MECHANISM

1. Isotype Heterojunction (n-n or p-p junctions)

- Both materials have the same doping type.
- Used in high-speed transistors.
- Example: GaAs/InGaAs (n-n heterojunctions) in High-electron-mobility transistor (HEMTs).

2. Anisotype Heterojunction (p-n heterojunctions)

- The materials have opposite doping types.
- Used in high-efficiency solar cells, LEDs, and laser diodes.
- Example: GaAs (p) / AlGaAs (n) in heterojunction bipolar transistors (HBTs).

BASED ON MATERIAL COMPOSITION

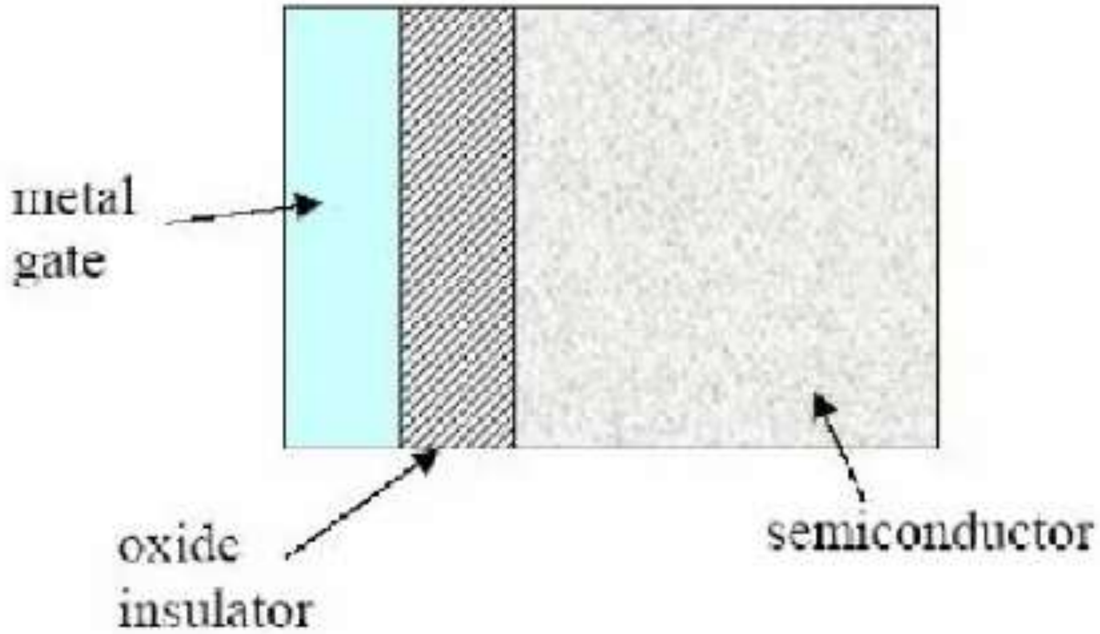
1. **Homovalent Heterojunction**
   - Both materials belong to the same semiconductor group but have different compositions.
   - Example: Si/SiGe.
2. **Heterovalent Heterojunction**
   - The materials belong to different semiconductor families with different valencies.
   - Example: GaAs/ZnSe.

METAL-OXIDE-SEMICONDUCTOR (MOS)

The **Metal-Oxide-Semiconductor (MOS)** structure is a fundamental component of modern electronic devices, particularly in MOSFETs. MOS structure is used for studying charge accumulation, depletion, and inversion at the semiconductor-oxide interface.

It consists of three main layers:

1. **Metal (Gate Contact):** Typically made of aluminum or heavily doped polysilicon. This layer acts as the gate electrode in transistors.
2. **Oxide (Insulating Layer):** A thin layer of silicon dioxide (SiO_2) or high-k dielectric material that insulates the gate from the semiconductor.
3. **Semiconductor (Substrate):** Usually silicon (Si), though other materials like gallium arsenide (GaAs) or silicon carbide (SiC) can be used.



OPERATION OF MOS STRUCTURE

MOS structures operate in three different modes based on the applied gate voltage:

1. **Accumulation:**
   - For a **p-type substrate**, applying a negative voltage to the gate attracts holes to the oxide-semiconductor interface. This increases carrier concentration at the surface.
2. **Depletion:**
   - A small positive voltage on the gate repels holes from the interface, creating a depletion region. This region is nearly devoid of mobile charge carriers.
3. **Inversion:**
   - A higher positive voltage attracts electrons (minority carriers in p-type material) to the interface. This forms an **inversion layer**, enabling conduction (essential for MOSFET operation).

ADVANTAGES OF MOS TECHNOLOGY

1. Low power consumption (used in CMOS circuits).
2. High integration density (basis of VLSI technology).
3. Scalability for advanced semiconductor devices.

APPLICATIONS OF MOS

MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors are used in

1. **Digital Circuits**: Used in logic gates, microprocessors, and memory devices.
2. **Analog Circuits**: Used in amplifiers, voltage regulators, and signal processing circuits.
3. **Power Electronics**: High-power MOSFETs are used in power supplies, motor controllers, and switching applications.

APPLICATIONS OF MOS

CMOS (Complementary MOS) Technology

- Used in modern microprocessors, microcontrollers, and digital logic circuits due to low power consumption.
- Found in smartphones, laptops, and embedded systems.

Dynamic Random Access Memory (DRAM)

- Uses MOS capacitors and transistors to store data.

Solar Cells

- MOS structures are used in photovoltaic applications for high-efficiency solar cells.

Radio Frequency (RF) Circuits

- MOS transistors are used in RF amplifiers and communication circuits.

Biosensors

- MOS-based sensors detect biological molecules, widely used in medical diagnostics.

MOLECULAR AND POLYMERIC SEMICONDUCTING MATERIALS

Introduction to Organic Semiconductors

- Organic semiconductors are carbon-based materials that exhibit semiconducting properties.
- They are used in flexible electronics, organic solar cells, OLEDs, and organic field-effect transistors (OFETs).

Two main types:

1. **Molecular semiconductors**
2. **Polymeric semiconductors**

Molecular semiconductors: Composed of small organic molecules with conjugated structures (alternating single and double bonds). Exhibit semiconducting properties due to charge delocalization.

Examples:

Pentacene – High charge carrier mobility, used in OFETs.

Rubrene –high photoluminescence and carrier transport.

Fullerenes – Used as electron acceptors in organic photovoltaics.

MOLECULAR AND POLYMERIC SEMICONDUCTING MATERIALS

Polymeric Semiconductors: Long-chain conjugated polymers that exhibit semiconducting behavior ideal for flexible and printable electronics.

Examples: Poly(3-hexylthiophene) – Used in organic solar cells. **Poly(p-phenylene vinylene) (PPV)** – Common in OLEDs.

Applications

1. **Organic Solar Cells** – Bulk heterojunction cells using polymer/molecular blends.
2. **Organic Light-Emitting Diodes** – Used in display and lighting technologies.
3. **Organic Field-Effect Transistors** – Used in flexible electronics and sensors.
4. **Wearable and Printed Electronics** – Flexible circuits and bioelectronics.
5. **Biosensors** – Medical diagnostics and environmental monitoring.

- Molecular and polymeric semiconductors are crucial for next-generation flexible and lightweight electronic devices.
- Molecular semiconductors offer high charge mobility, while polymeric semiconductors provide mechanical flexibility and processability.
- Ongoing research aims to improve stability, charge transport, and efficiency for various applications in optoelectronics and bioelectronics.

SOLAR CONCENTRATORS, SEMICONDUCTORS, QUANTUM DOTS IMPORTANCE OF SEMICONDUCTORS IN DEVICE TECHNOLOGIES

Importance of Semiconductors in Device Technologies

- **Transistors & Integrated Circuits (ICs)**: The foundation of modern computers, smartphones, and microelectronics.
- **Photovoltaics (Solar Cells)**: Convert sunlight into electricity using semiconductor materials like silicon and perovskites.
- **Light Emitting Diodes & Lasers**: Used in displays, optical communication, and lighting.
- **Sensors & Detectors**: Semiconductor-based sensors are used in medical devices, environmental monitoring, and IoT applications.
- **Power Electronics**: Efficient power management in EVs, grid systems, and industrial automation.

SOLAR CONCENTRATORS, SEMICONDUCTORS, QUANTUM DOTS IMPORTANCE OF SEMICONDUCTORS IN DEVICE TECHNOLOGIES

Semiconductors in Solar Concentrators

Solar concentrators use lenses or mirrors to focus sunlight onto high-efficiency semiconductor solar cells, improving power output.

- **Multi-junction Solar Cells**: Made of semiconductor layers like GaAs (Gallium Arsenide) to absorb different wavelengths of light.
- **Quantum Efficiency**: Semiconductor materials enhance photon absorption, leading to better energy conversion.
- **Concentrated Photovoltaics (CPV)**: Use of III-V semiconductor materials for high efficiency.

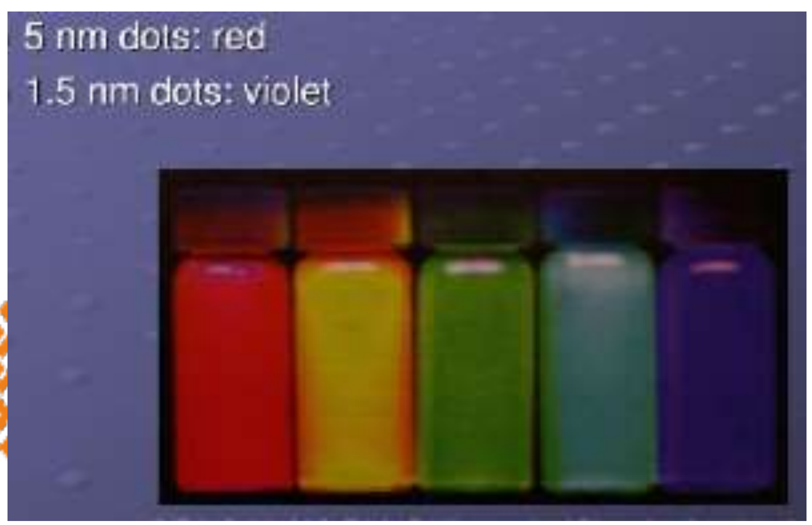
QUANTUM DOTS IN SEMICONDUCTOR TECHNOLOGY

1. Quantum Dots (QDs) are nanoscale semiconductor particles (typically 2-10 nm in size) that exhibit unique quantum mechanical properties.

2. Their behavior is governed by quantum confinement effects, which result in discrete energy levels.

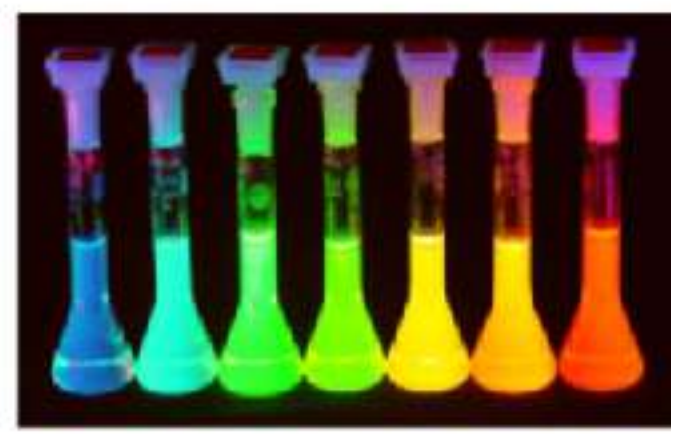
3. QDs can emit specific wavelengths of light depending on their size, making them highly tunable for various applications.

Ex: CdSe, PbSe, PbTe, InP



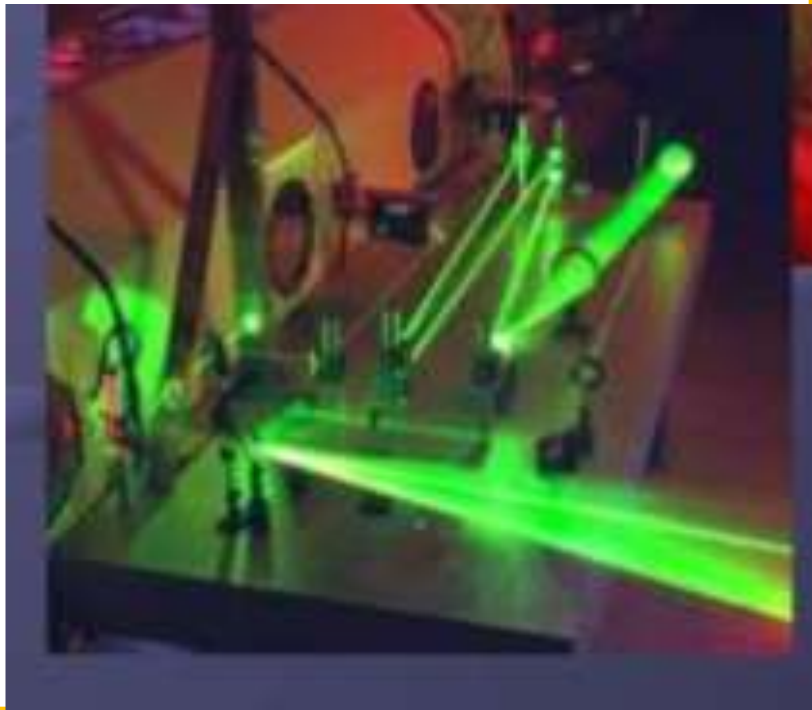
Tuning Quantum Dots

By changing size, shape, and composition, quantum dots can change their absorptive and emissive properties dramatically



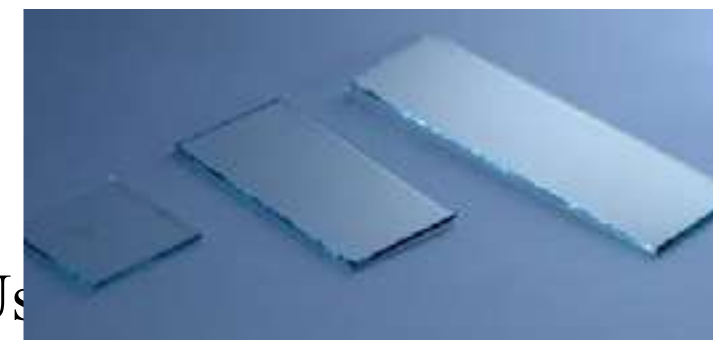
DEVICE APPLICATION OF QDS

1. Lasers with active area based on QDs
2. Light-Emitting Device (LED) based on QDs
3. Quantum Dots Solar Cells
4. Biosensors and Imaging
5. Memory elements
6. Photo detectors
7. Lasers



ADVANCED TRANSPARENT CONDUCTING SUBSTRATES

- Transparent conducting substrates (TCS) are materials that exhibit both **high optical transparency** and **good electrical conductivity** at visible wavelengths.
- They are essential for applications in solar cells, organic light-emitting devices, smart windows, and touch screens for the flexible wearable.
- Advanced TCS materials focus on overcoming limitations like brittleness, cost, and limited availability of traditional materials.



Conventional Transparent Conducting Materials

- **Indium Tin Oxide (ITO)-** High conductivity and transparency. Us solar cells. **Limitations**: Brittle, expensive due to indium scarcity, and not flexible.
- **Fluorine-doped Tin Oxide (FTO)** – Used in dye-sensitized solar cells.
- **Aluminum-doped Zinc Oxide (AZO)** – More abundant and cost-effective than ITO.

ADVANCED TRANSPARENT CONDUCTING SUBSTRATES

a) Metal-Based Conductors

1. Ultra-Thin Metal Films (Ag, Cu, Au)

- Offer high electrical conductivity, can be made transparent with proper thickness (~10 nm).

2. Metal Nanowires (AgNW, CuNW)

- Flexible and highly conductive networks. They are used in next-gen touch screens and OLEDs.

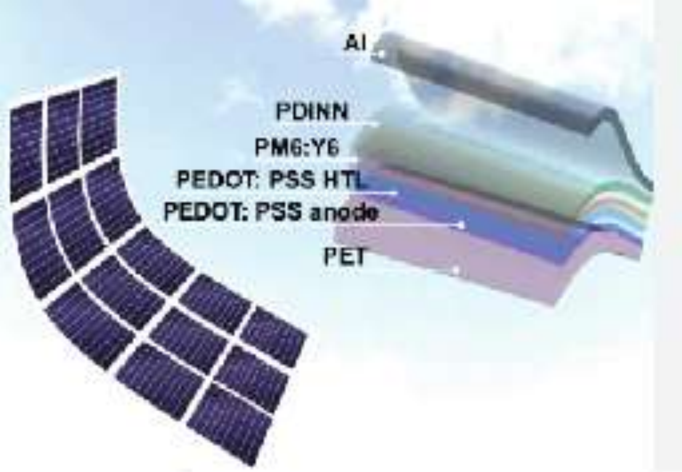
b) Carbon-Based Materials

1. Graphene and Carbon Nanotubes (CNTs)

- High transparency (~97%) and superior flexibility. Chemically stable and can be synthesized via CVD.

Challenges: Relatively lower conductivity than metal films, difficult integration.

ADVANCED TRANSPARENT CONDUCTING SUBSTRATES



c) Conducting Polymers

- **PEDOT:PSS (Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate)**
- Used in flexible and wearable electronics. **Challenges**: Lower conductivity than metal-based alternatives.

d) Hybrid and Composite Materials

1. Metal Nanowire-Graphene Hybrids

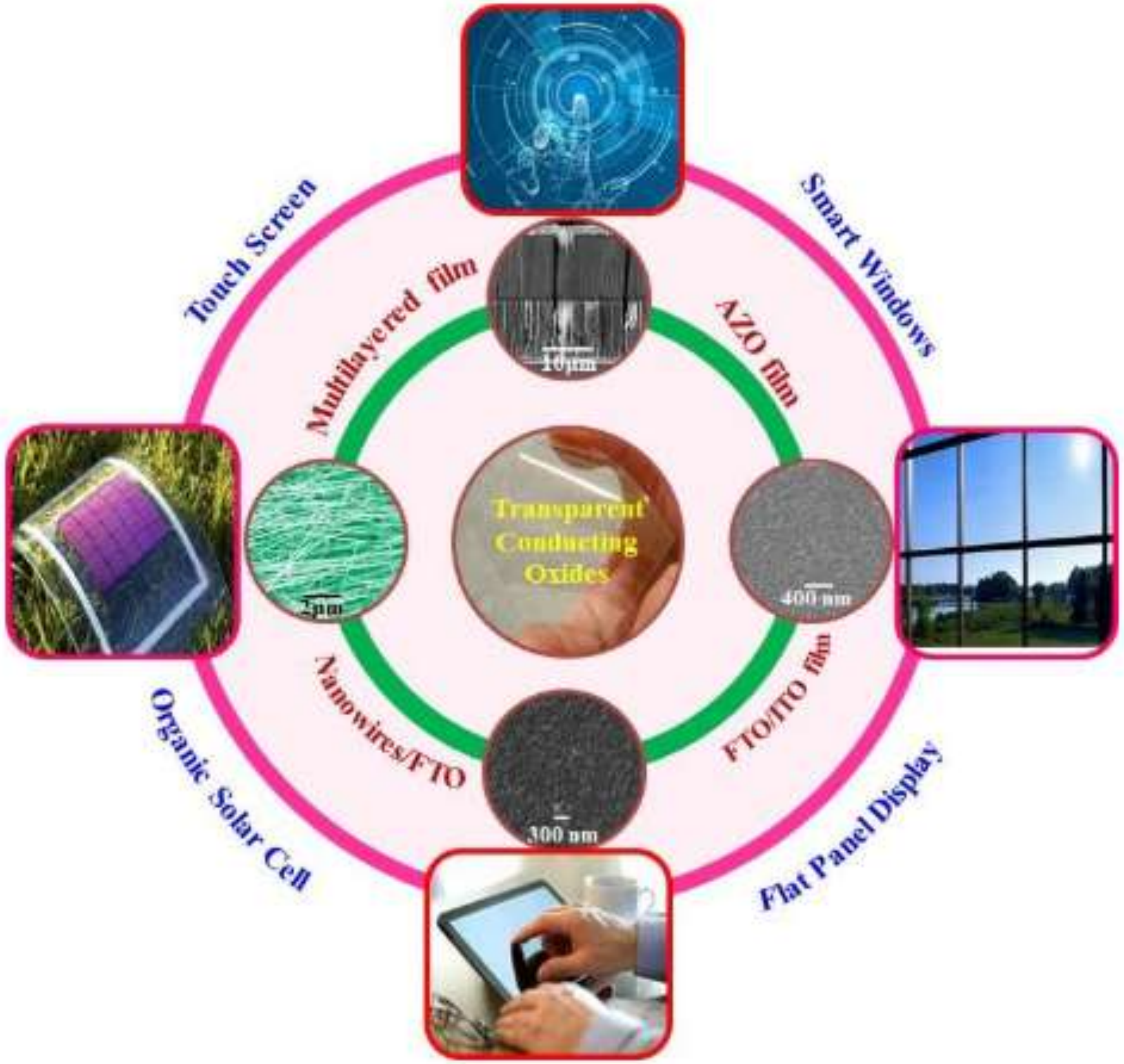
- Combine high conductivity of metals with flexibility of graphene.

2. Metal Oxide-Polymer Composites

- Improve mechanical stability and performance.

TCFS APPLICATIONS

- **Flexible Displays & Wearables** – Used in foldable smart phones, AR/VR screens.
- **Solar Cells** – Transparent electrodes for thin-film and perovskites solar cells.
- **Touch screens & OLEDs** – Replacements for ITO in touch-sensitive devices.
- **Smart Windows** – For energy-efficient glass that controls light transmission.



THIN FILM DEVICE TECHNOLOGIES

Thin film - A materials with a thickness in the range of a nanometer to a few micrometers.

Thin film device technologies uses ultra-thin material layers for creating electronic, optical, and energy-related devices by different deposition techniques. These technologies are widely used in semiconductors, photovoltaics, sensors, and display technologies.

Thin Film Deposition Techniques

1. **Physical Vapor Deposition (PVD)**: Includes evaporation and sputtering methods.
2. **Chemical Vapor Deposition (CVD)**: Used for semiconductor fabrication and coatings.
3. **Atomic Layer Deposition (ALD)**: Offers precise control over film thickness.
4. **Spin Coating & Dip Coating**: Used for organic and polymer thin films.

It uses materials like

1. **Semiconductors**: Si, GaAs, CdTe, Perovskites
2. **Metals**: Au, Ag, Al, Cu
3. **Dielectrics & Insulators**: SiO_2, Al_2O_3, HfO_2
4. **Transparent Conductive Oxides**: ITO (Indium Tin Oxide), ZnO

Advantages of Thin Film Devices

1. Lightweight and flexible designs.
2. Lower material consumption and cost-effectiveness.
3. Enhanced performance in certain applications (e.g., higher efficiency in solar cells).
4. Compatibility with large-area deposition techniques for scalable manufacturing.

THIN FILM DEVICE TECHNOLOGIES

Effects of size reduction - Size reduction in thin-film device technologies has several significant effects, impacting performance, fabrication, and reliability.

Enhanced Performance

- **Higher Speed**: Reduced dimensions lead to lower capacitance and resistance, improving the speed of electronic devices.
- **Lower Power Consumption**: Smaller devices require less power, improving efficiency in applications like mobile electronics.
- **Better Frequency Response**: Miniaturization enhances the operating frequency of devices, making them suitable for high-speed applications.

Increased Integration Density

- **More Components per Chip**: Shrinking device sizes allow for more transistors or circuit elements to be integrated onto a single chip.
- **Higher Functionality**: Enables the development of complex and multifunctional devices.

THIN FILM DEVICE TECHNOLOGIES

Effects of size reduction

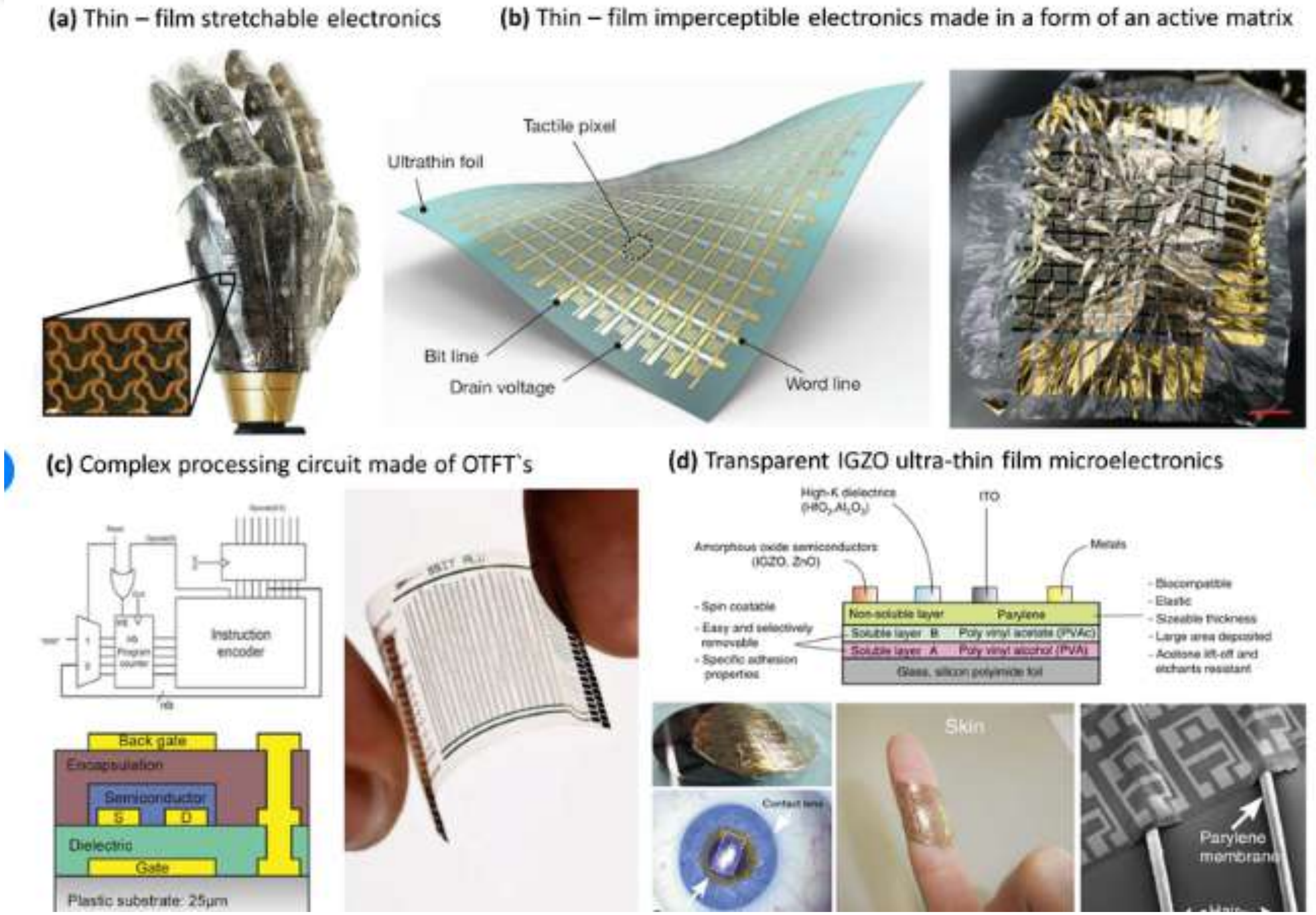
Fabrication and Reliability Concerns

- **Process Complexity**: Advanced lithography and etching techniques are required to achieve ultra-small feature sizes.
- **Defect Sensitivity**: Smaller devices are more susceptible to defects, impacting yield and reliability.
- **Heat Dissipation Issues**: High integration density can lead to localized heating, affecting device lifetime and performance.

Advancements in Emerging Technologies

- **Flexible Electronics**: Thin-film size reduction supports the development of flexible and wearable electronics.
- **Nanotechnology Integration**: Enables the use of novel materials like graphene, carbon nanotubes, and 2D materials for next-generation devices.
- **Low-Power and IoT Applications**: Miniaturization is crucial for energy-efficient sensors and IoT-enabled devices.

THIN FILM DEVICE TECHNOLOGIES



Application-Specific Advantages

1. **Flexible Electronics**: Thin and compact designs are ideal for flexible and wearable devices.
2. **Optoelectronics**: Miniaturized thin-film LEDs, photodetectors, and solar cells achieve higher efficiency and integration.
3. **Memory and Storage**: Thin-film memory devices, such as resistive RAM (ReRAM) and phase-change memory (PCM), benefit from size reduction for higher storage density.