Sustainable Solar Energy Technologies & Job Opportunities

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2. 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, quantum dots importance of semiconductors in device technologies, Effects of size reduction – thin film device technologies.

Semiconductor processing- Industrial processes and challenges, Solar grade semiconductors preparation

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.

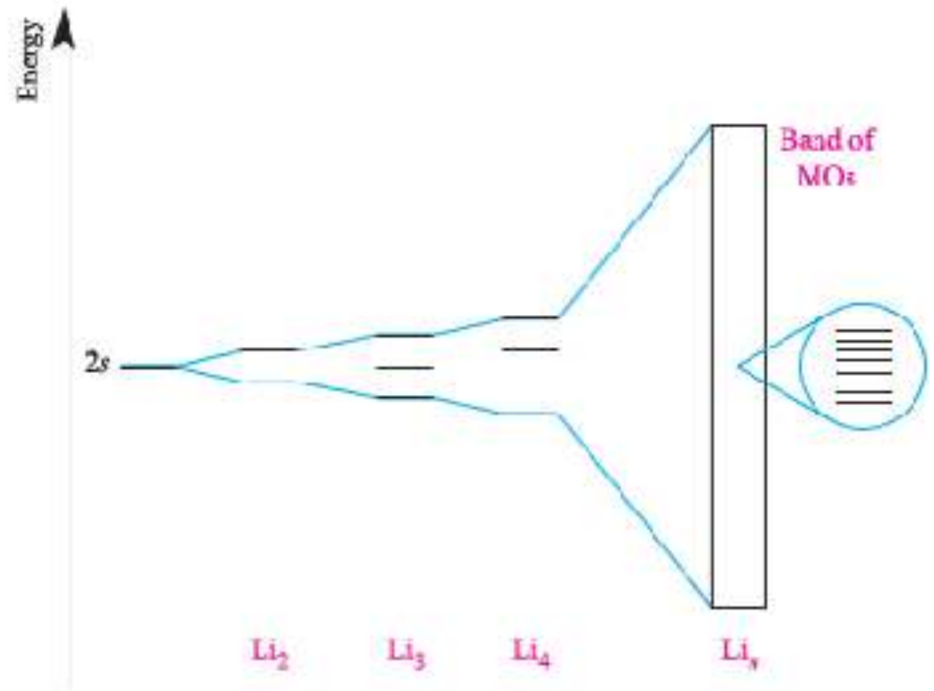
Materials can be divided into 3 types based on the values of energy gap

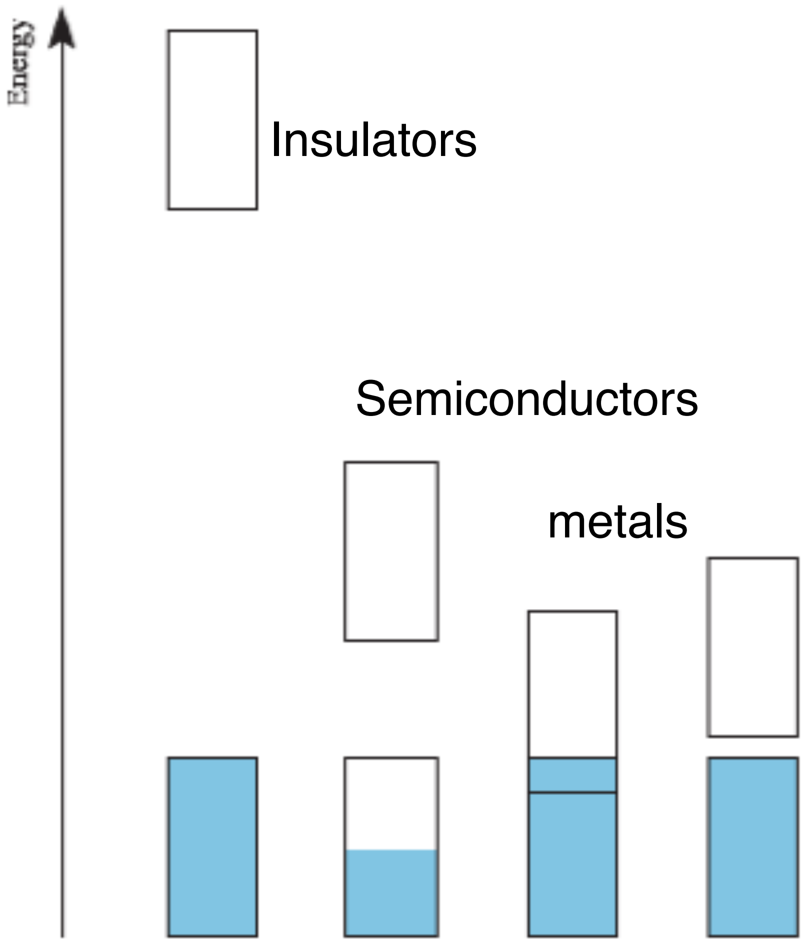
0 eV)

❖ **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)

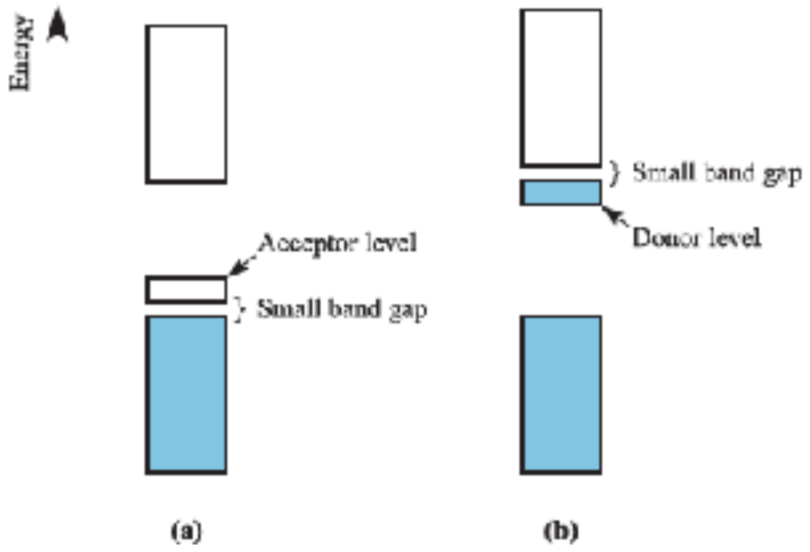
Band structures

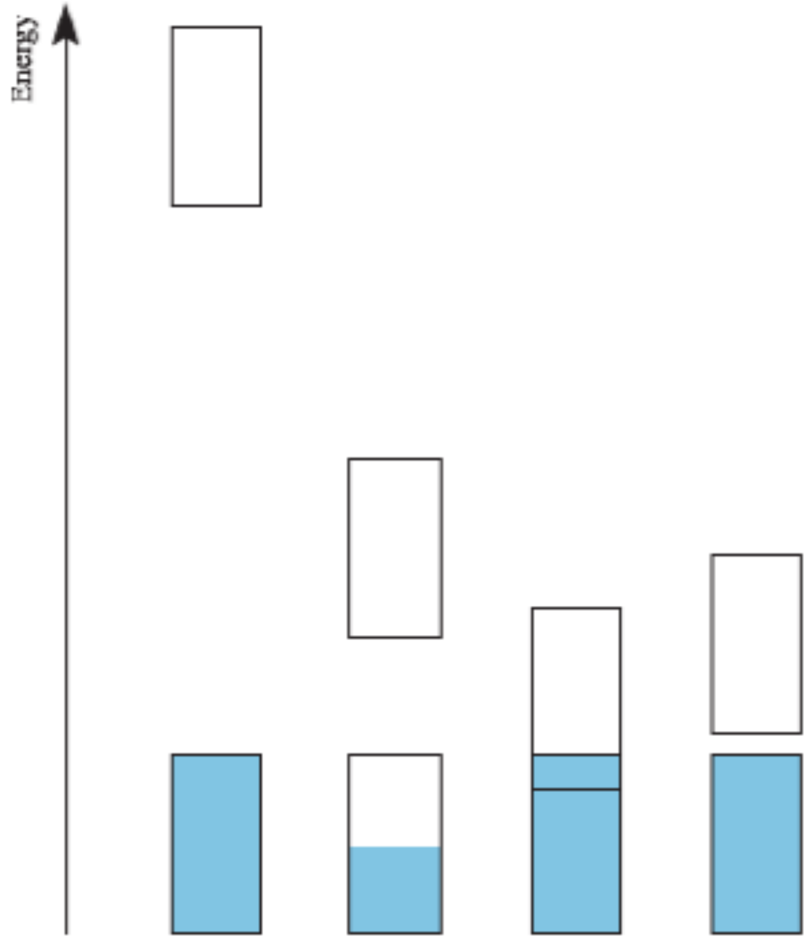




- ➢Energy level splitting in quantum matters – atoms , molecules, nanostructures
- ➢Band is collection of close lying energy levels of molecular orbitals(MO)
- ➢Energy gap depends on the HOMO and LUMO
- ➢Semiconductors band gap – 1 to 3.1 eV

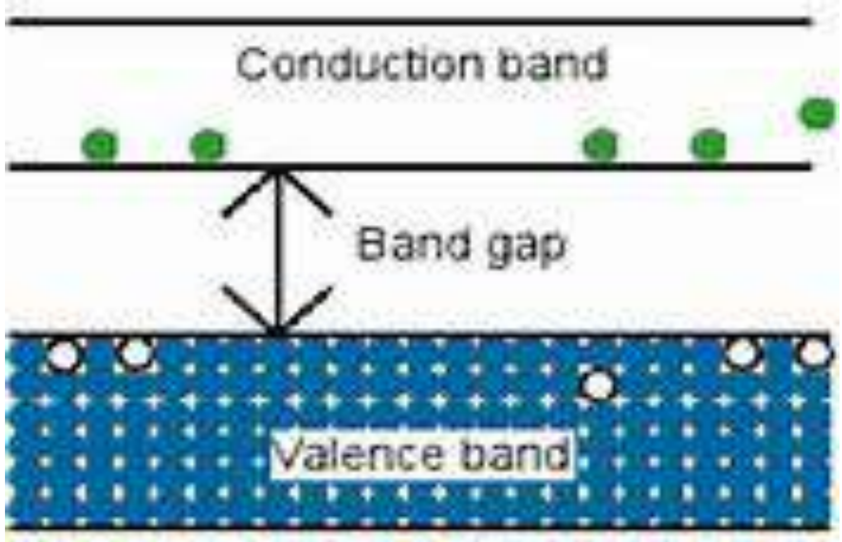
Band gap modulation in semiconductors

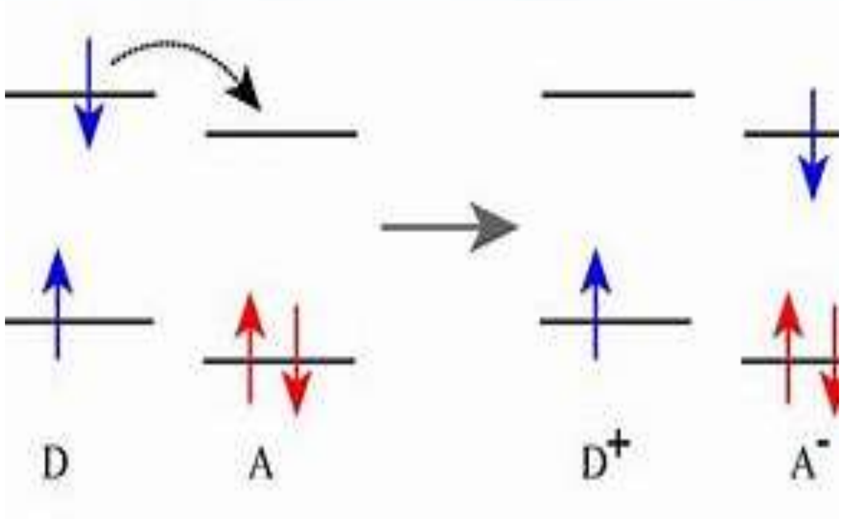


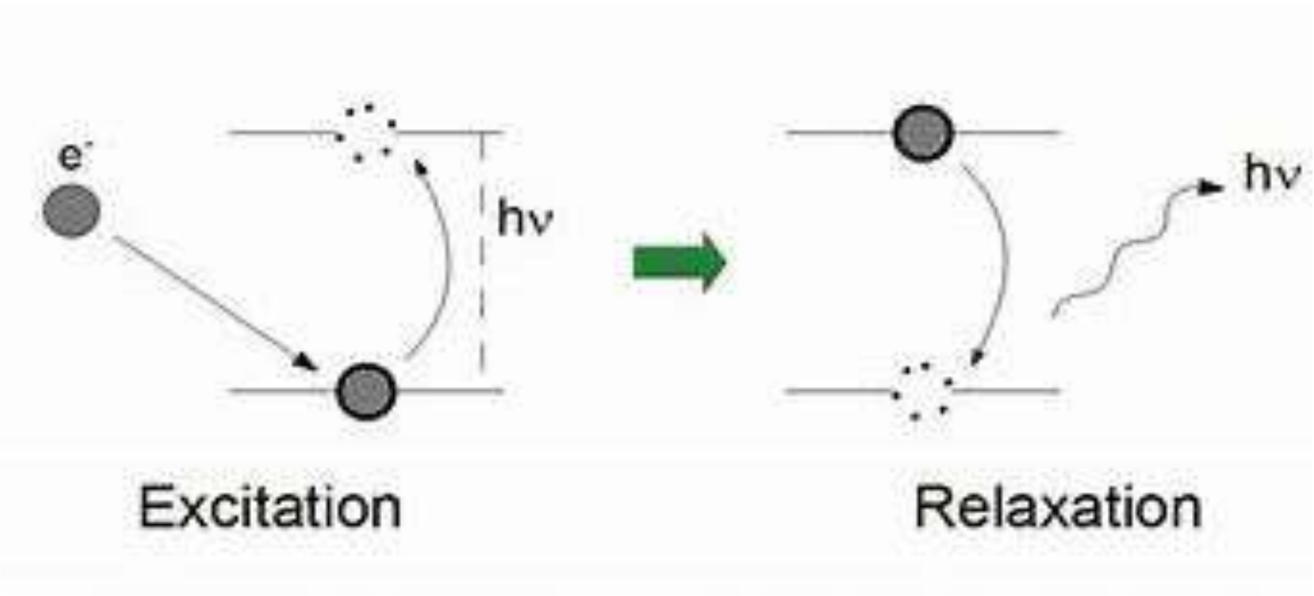


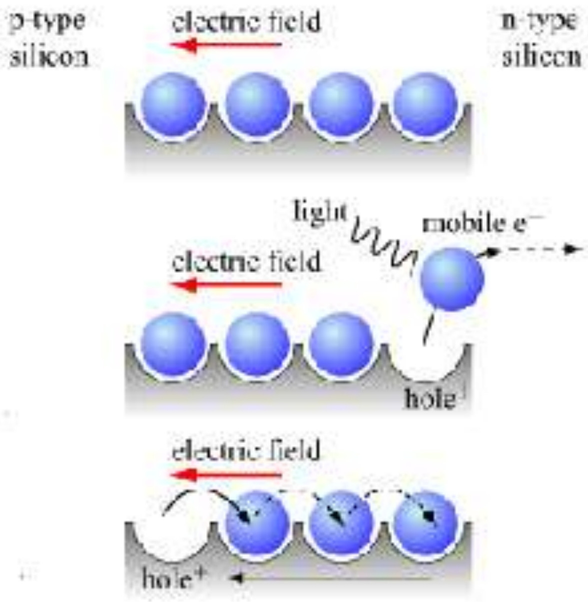
- ➢ a- p-type doping in silicon
- ➢ b – n-type doping in silicon
- ➢ Energy gap changes with doping
- ➢ Extent of doping should not be high

Electrons in matter – Charge transfer









BAND GAP MODULATION IN SEMICONDUCTORS

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.

SEMICONDCUTOR

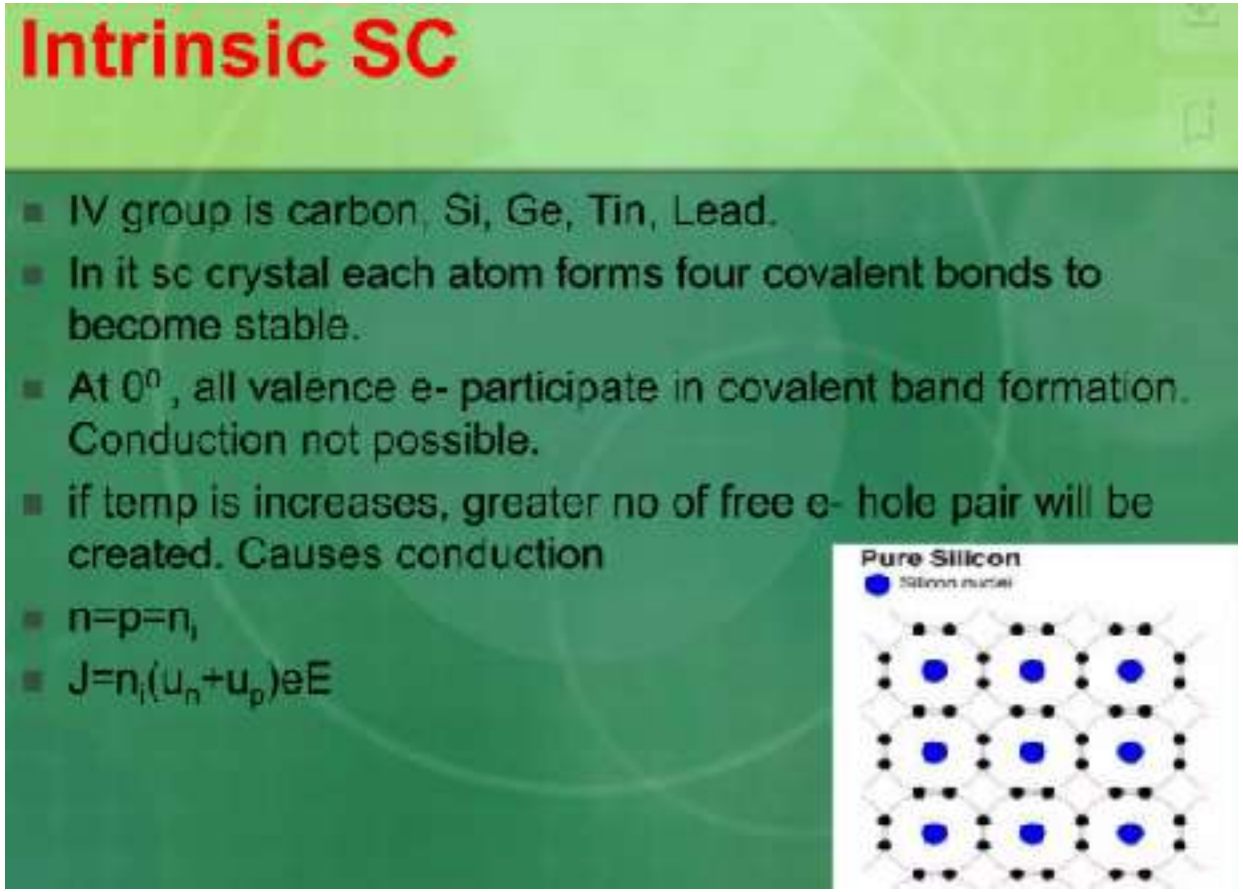
- Carrier generation can happen due to
- Photo excitation
- Electrical excitation
- Thermal excitation
- Absorption coefficient is higher for

Direct bandgap semiconductor, indirect

Bandgap has less absorption,(need thick

Films – Recombination will be higher)

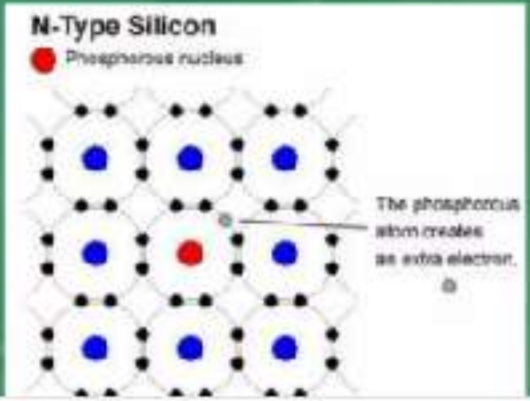
- Impact ionization



SEMICONDCUTOR

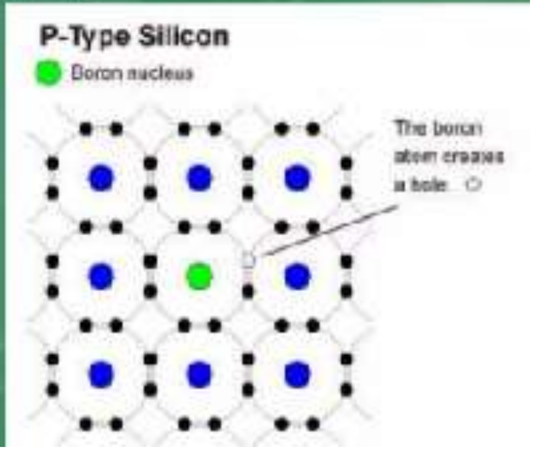
N type SC

- 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 $n_n \cdot p_n = n_i^2$
- Majority is e-
  minority is holes

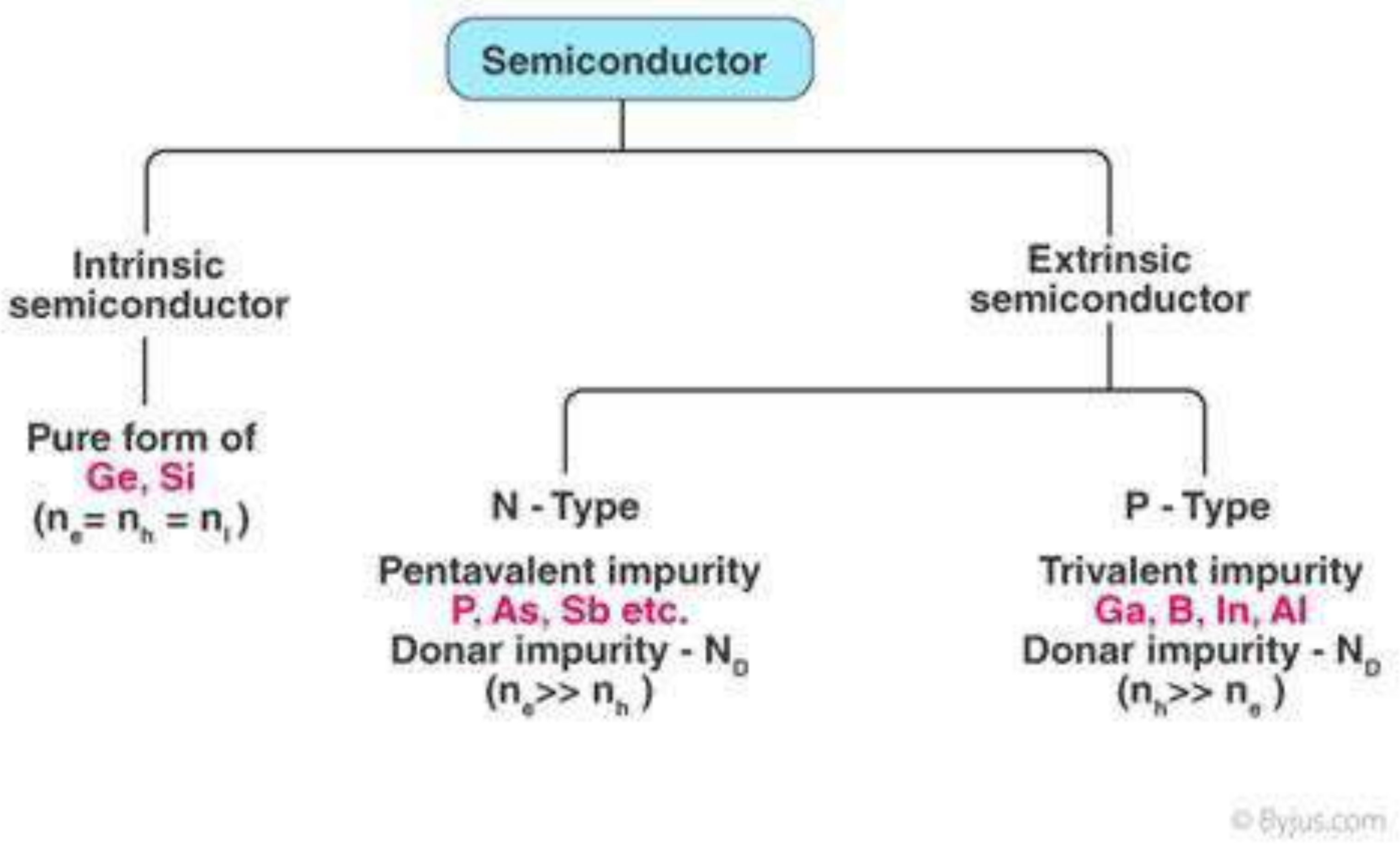


P type SC

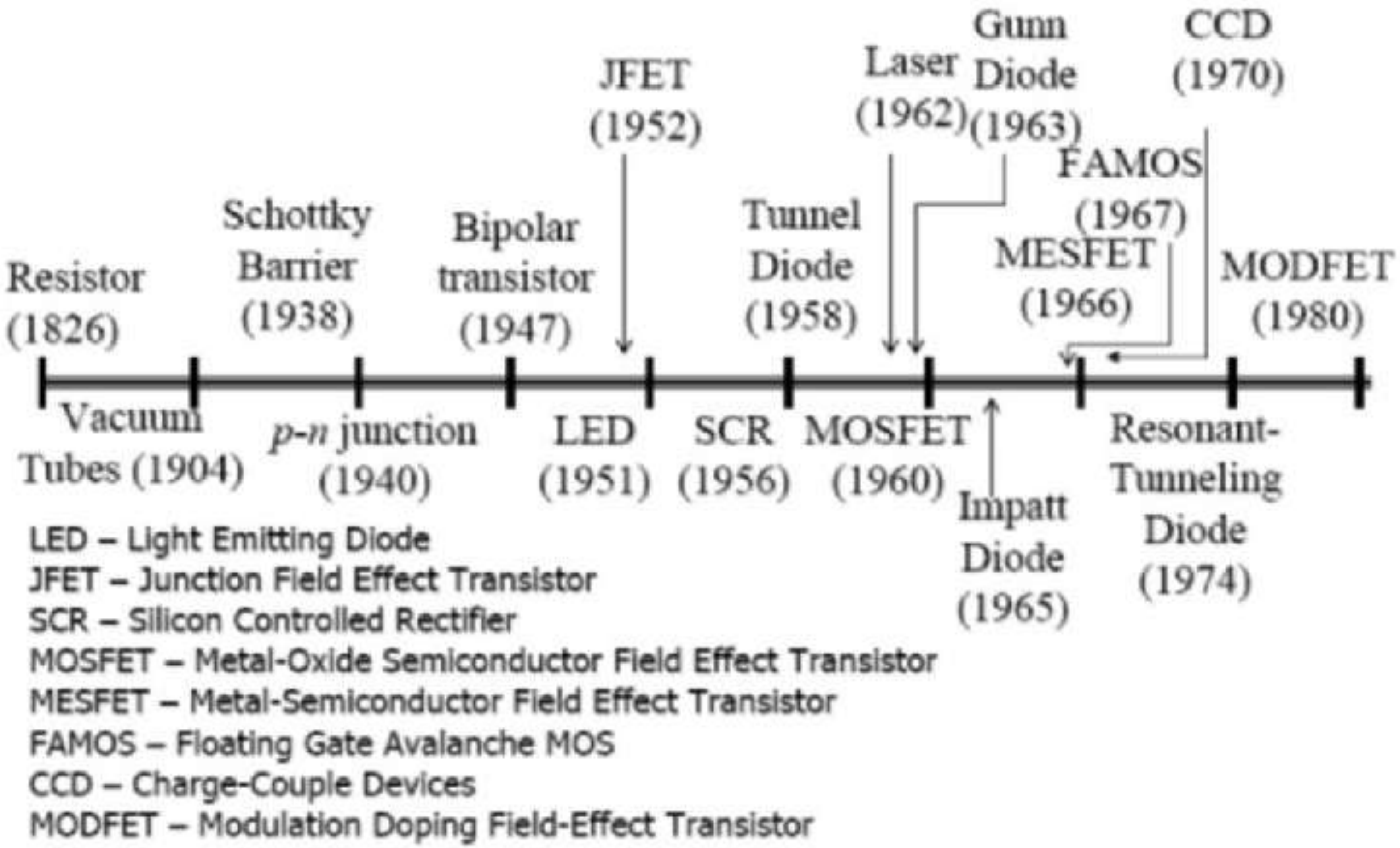
- 3^{rd} group B, Al, Ga.
- B forms 3 covalent bonds with Si and forms 4^{th} bond with hole formation.
- According to law of Nutrality $n_p + n_A = p_p$
- Mass action law $n_p \cdot p_p = n_i^2$
- Majority is holes
  minority is e^-

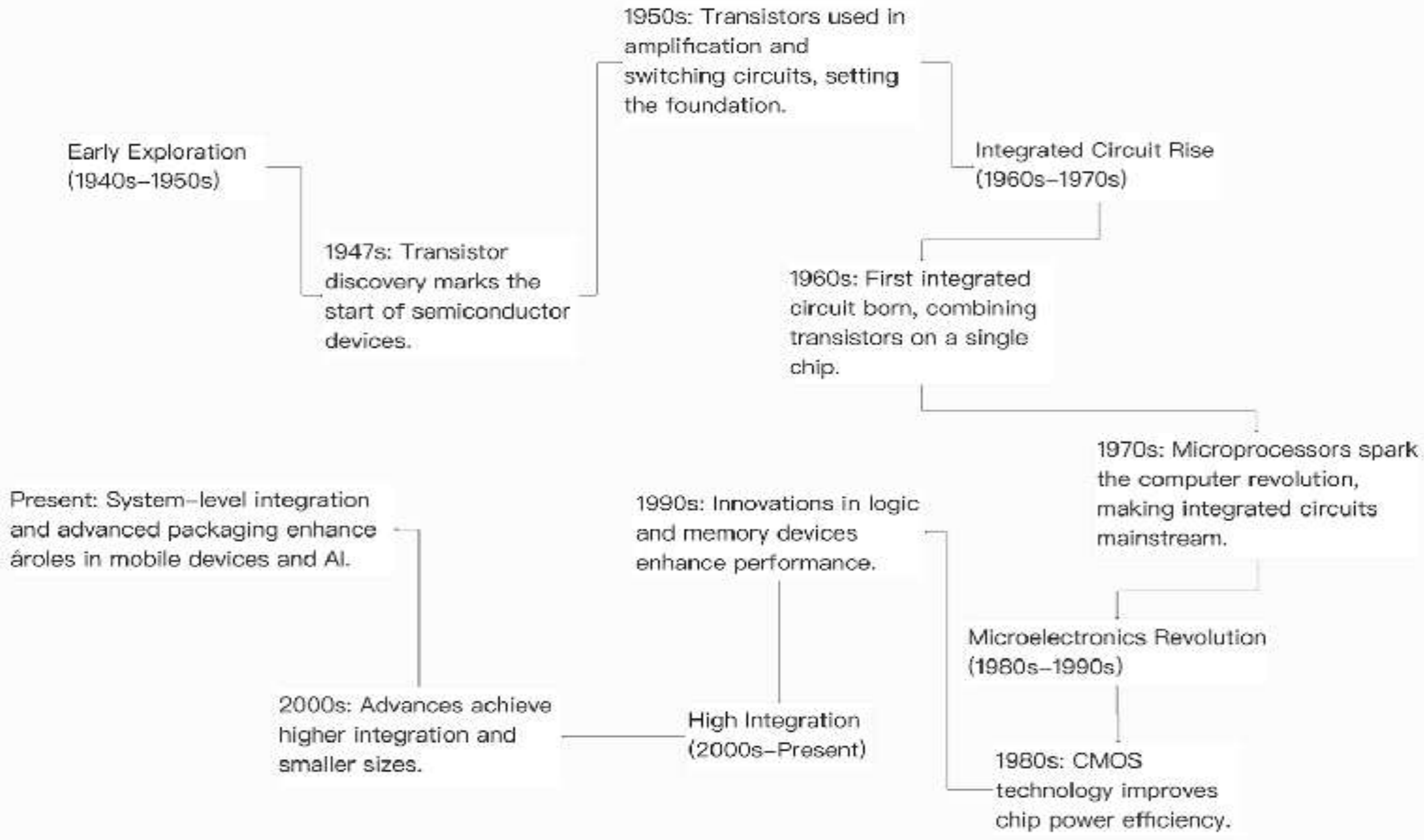


Types of Semiconductors



History of Semiconductor devices





Early Exploration (1940s–1950s)
1947s: Transistor discovery marks the start of semiconductor devices.
1950s: Transistors used in amplification and switching circuits, setting the foundation.
Integrated Circuit Rise (1960s–1970s)
1960s: First integrated circuit born, combining transistors on a single chip.
1970s: Microprocessors spark the computer revolution, making integrated circuits mainstream.
Microelectronics Revolution (1980s–1990s)
1980s: CMOS technology improves chip power efficiency.
1990s: Innovations in logic and memory devices enhance performance.
High Integration (2000s–Present)
2000s: Advances achieve higher integration and smaller sizes.
Present: System-level integration and advanced packaging enhance ároles in mobile devices and AI.

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.

Importance of semiconductor

- Band gap of materials govern the electronic transitions
- Crystallinity for long range charge transport
- Facile charge separation
- Low recombination rates
- Cheap materials and easy processability
- Broad range of spectral or energy absorption
- Heterostructures for efficient charge separation, wide band absorption in whole visible spectrum
- Improve incident photon conversion efficiency

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SILICON SINGLE CRYSTAL


Monocrystalline cell

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.

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.

Czochralski Method

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 types of semiconductors

- Elemental Semiconductors (Si, Ge)
- Binary semiconductors (copper oxides (CuO), Gallium Arsenide (GaAS), Titanium dioxide (TiO_2)
- Ternary semiconductors (Bismuth vanadates ($BiVO_4$), Copper indium selenides)

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. Crystallinity - Reduces recombination loss

- **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 based on size
- 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.

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.**

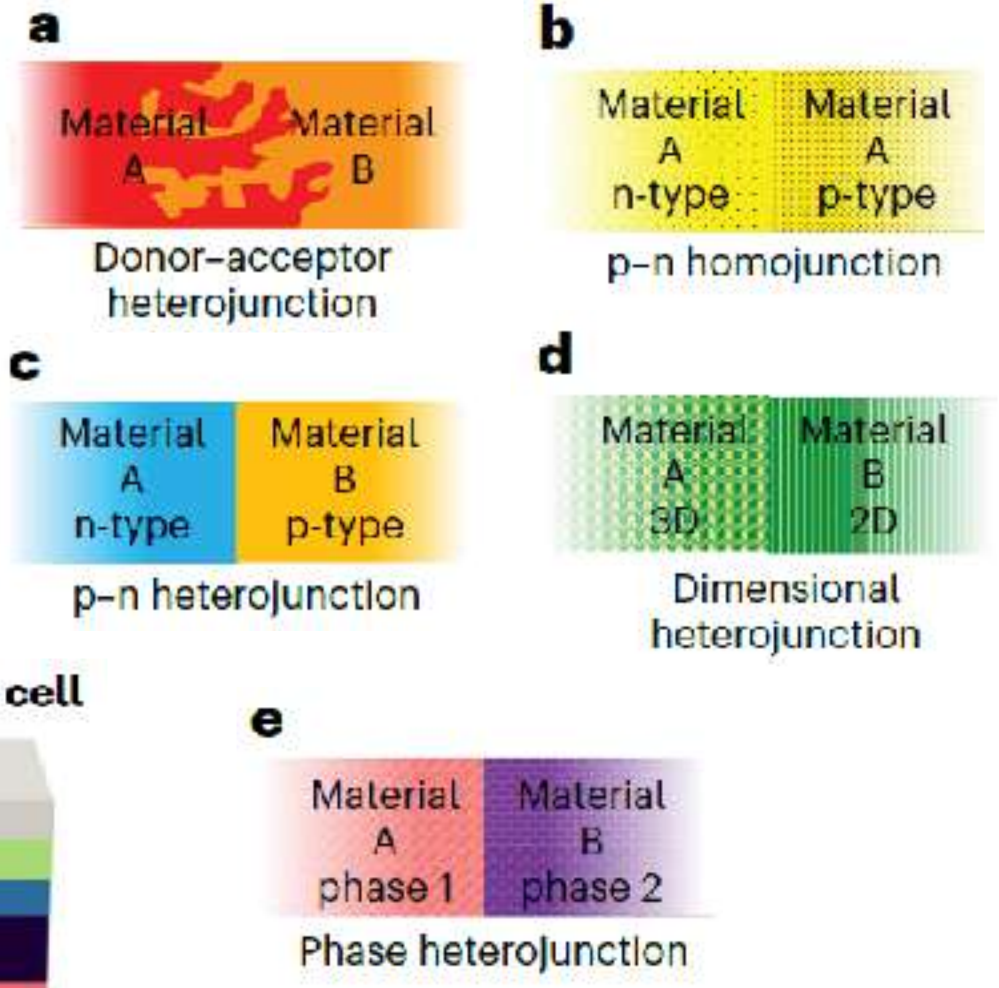
Formation the p-n Junction

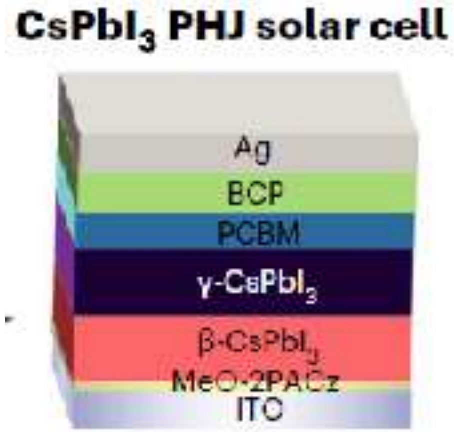
When p-type and n-type semiconductors are brought together. Electrons from the N-type region move into the P-type region, where they recombine with holes.

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.

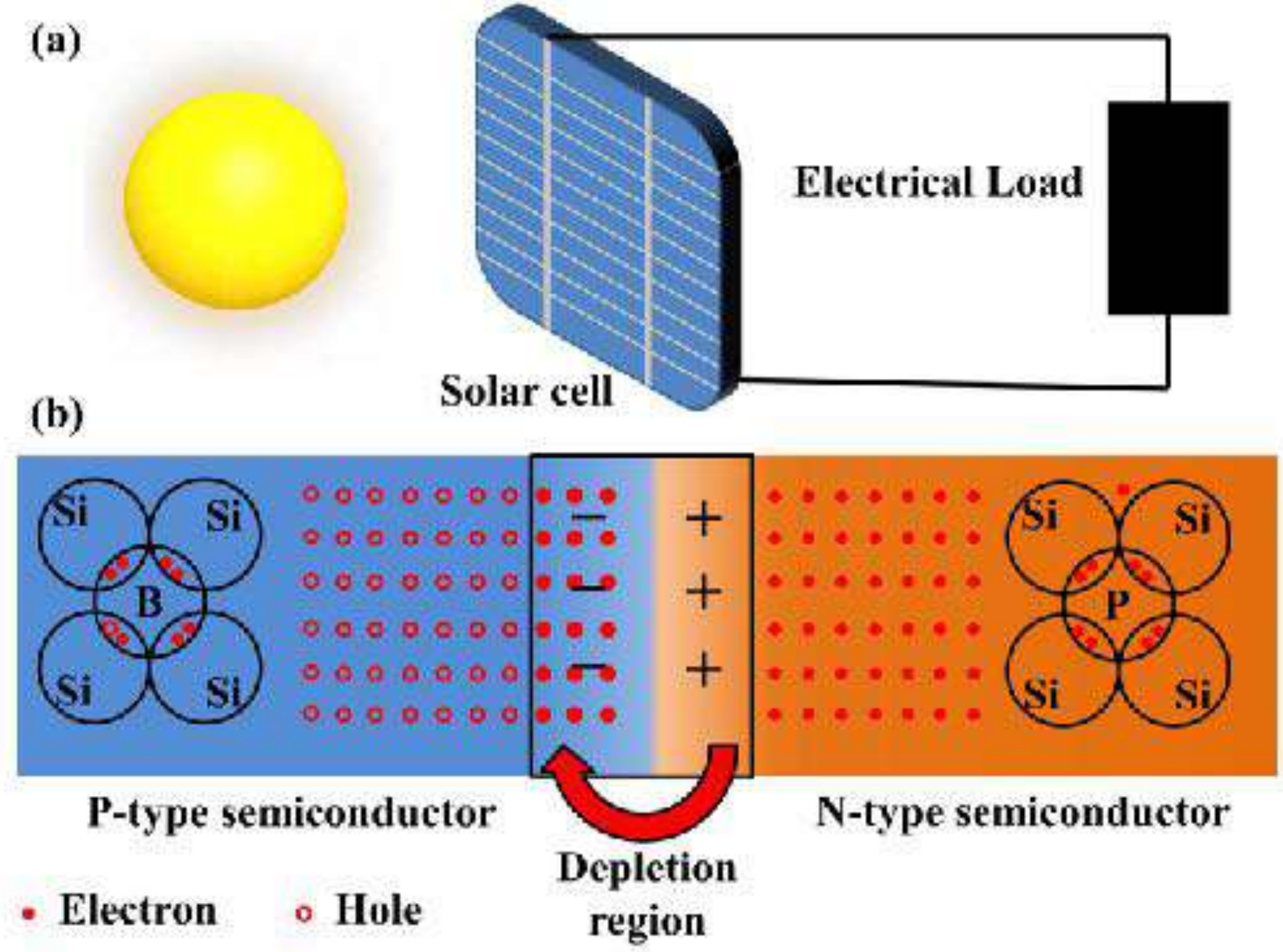
Different types of junctions in Photovoltaic systems

- Solar to electric (photovoltaics)
- Photon conversion efficiency
- Modern PV with Heterostructured junctions
- Increase in efficiency upto 43 % lab scale achieved
- Non silicon Pervoskite heterojunction next generation solar cell





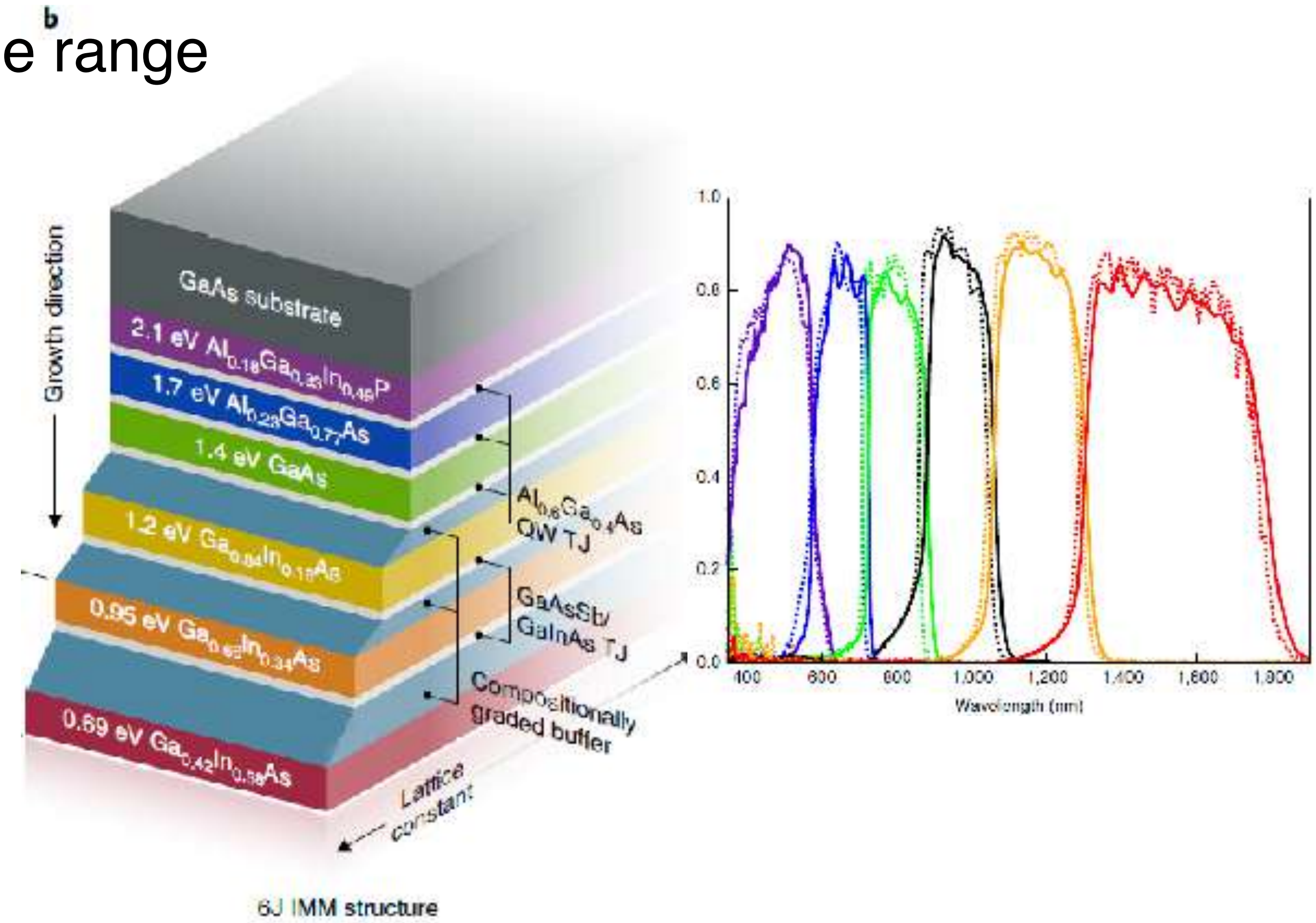
PV structure and operation



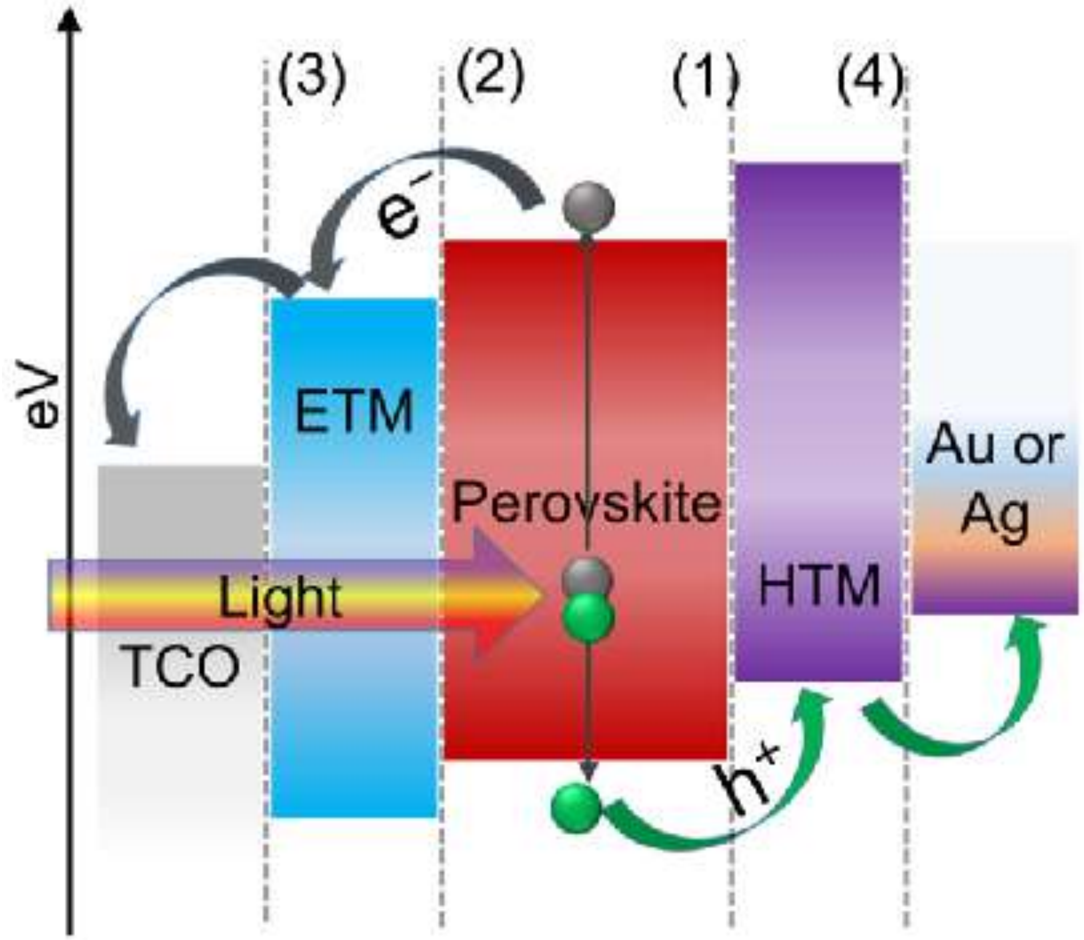
- Solar to electric (photovoltaics)
- P-type and n-type materials
- Potential barrier formation
- PB enhance charge separation
- Reduce recombination losses
- Efficiency improvements with other non silicon heterojunctions
- Broad visible light absorption

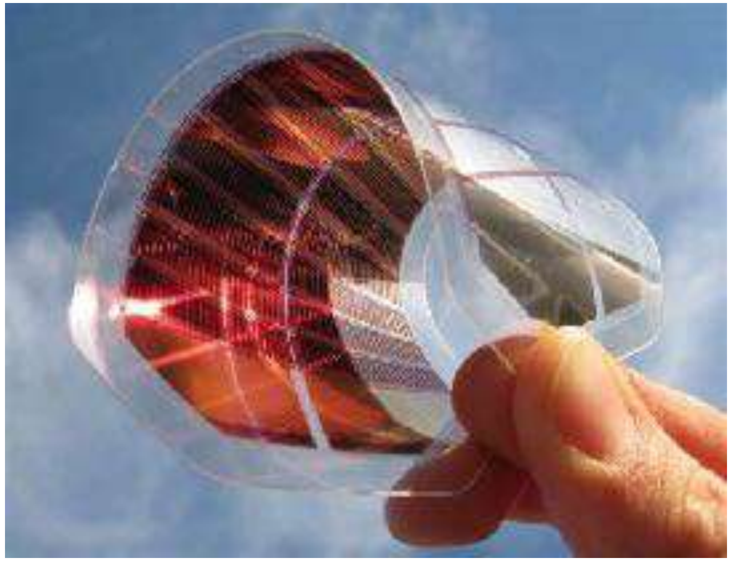
Heterojuction solar cell – 47 % lab efficiency -

- Wide absorption in visible range
- Multi band gap junctions
- Easy charge separation
- Crystalline thin film
- Increases the efficiency
- Nearly 47 % - lab scale



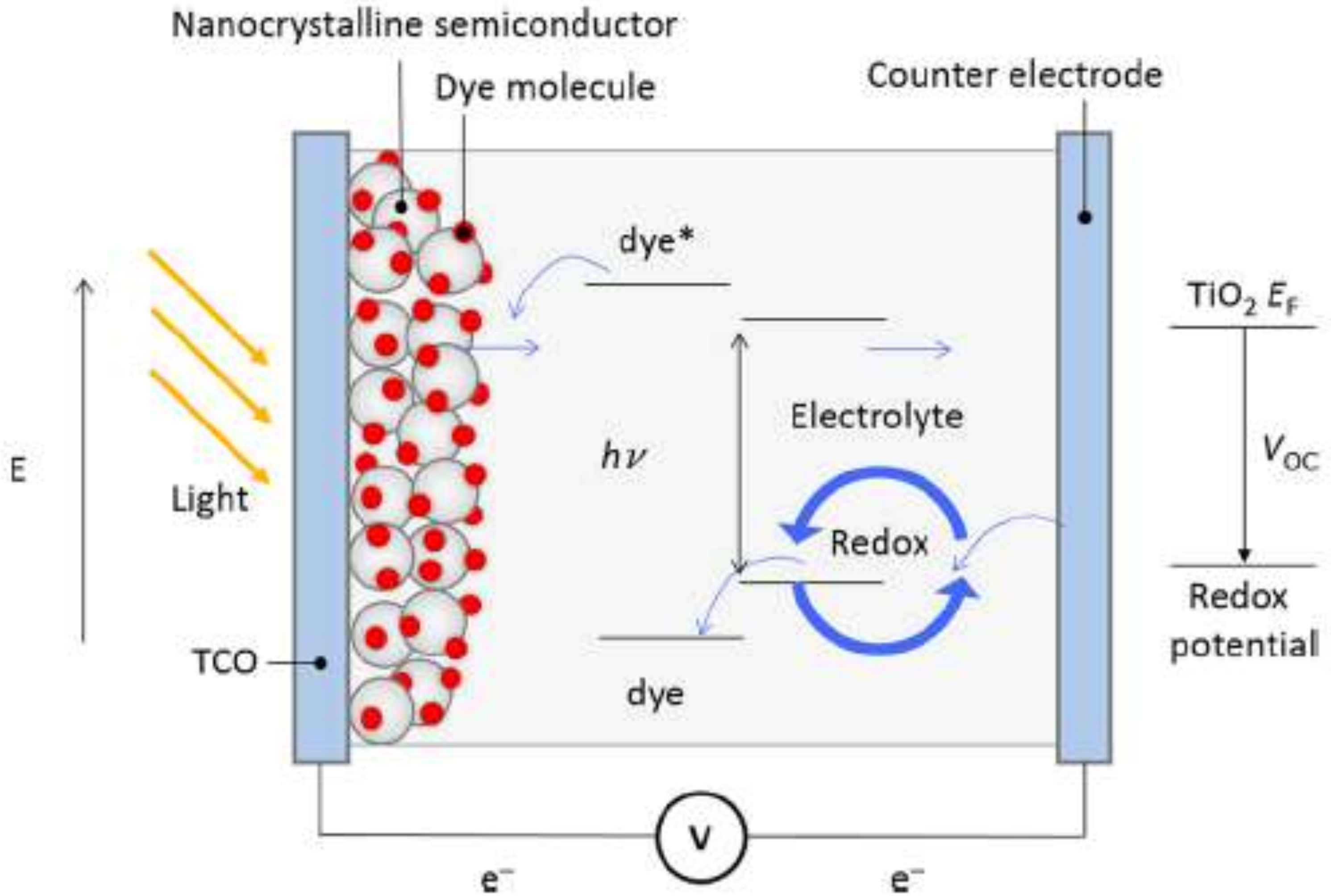
Perovskite the future Tandem solar cell



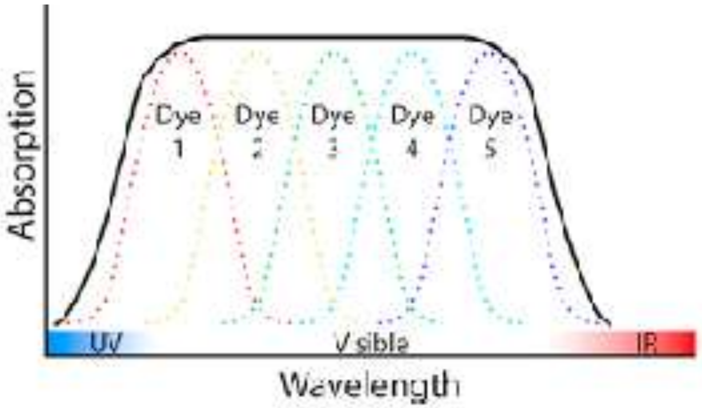


- Use flexible polymer as substrate
- Good charge separation with HTM and ETM
- Higher efficiency, band gap modulation
- Low cost material
- ETM- Electron transport materials
- HTM – Hole transport materials

Dye sensitized solar cell (DSSC) – Graetzel cell



Visible absorption by dyes

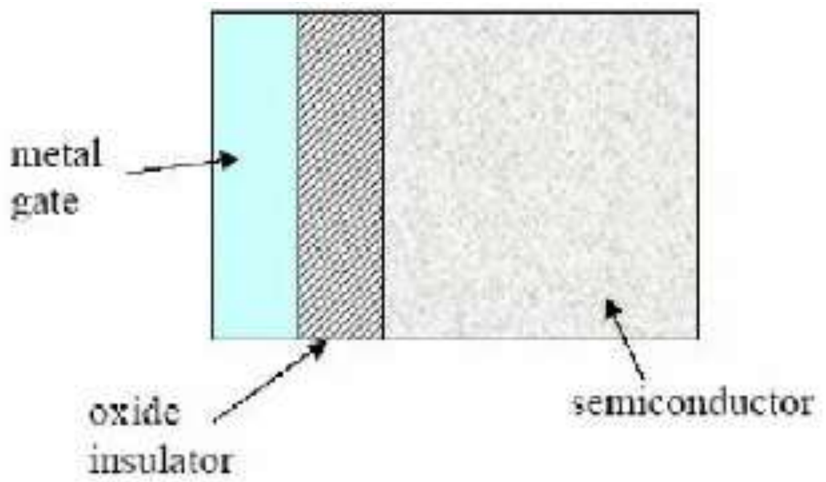


METAL-OXIDE-SEMICONDUCTOR (MOS)

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.

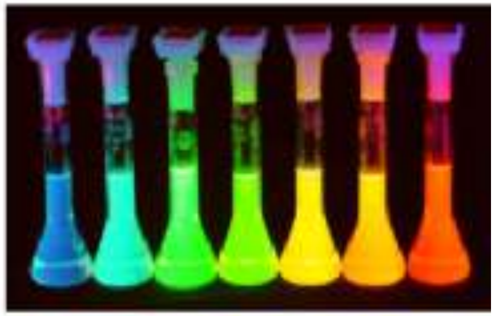
2. Their behavior is governed by quantum confinement effects, which result in discrete energy levels.

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

Ex: CdSe, PbSe, PbTe, InP

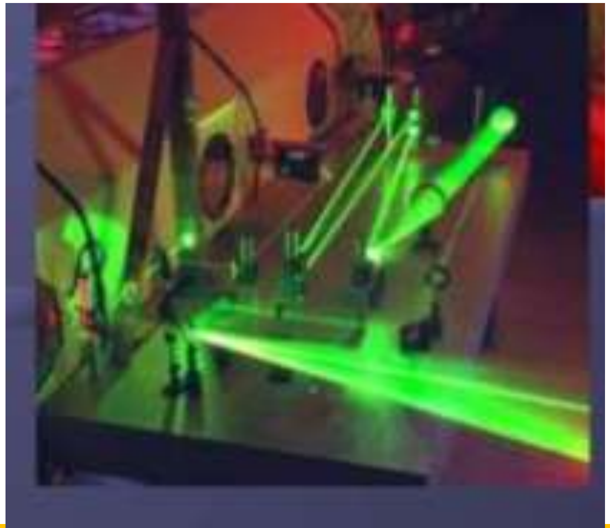
Tuning Quantum Dots

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



DEVICE APPLICATION OF QDS

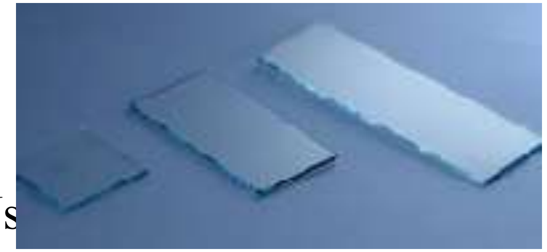
1. Lasers with active area based on QDs
2. Light-Emitting Device (LED) based on QDs
3. Quantum Dots Solar Cells
4. Biosensors and Imaging
5. Memory elements
6. Photo detectors
7. Lasers



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.

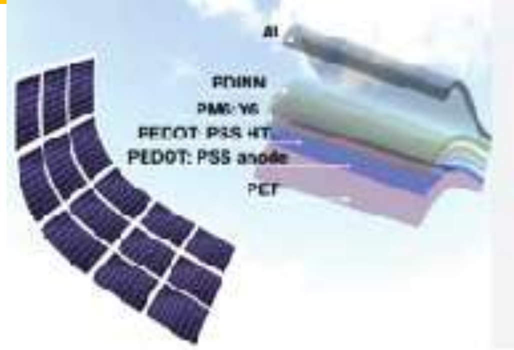
b) **Carbon-Based Materials**

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

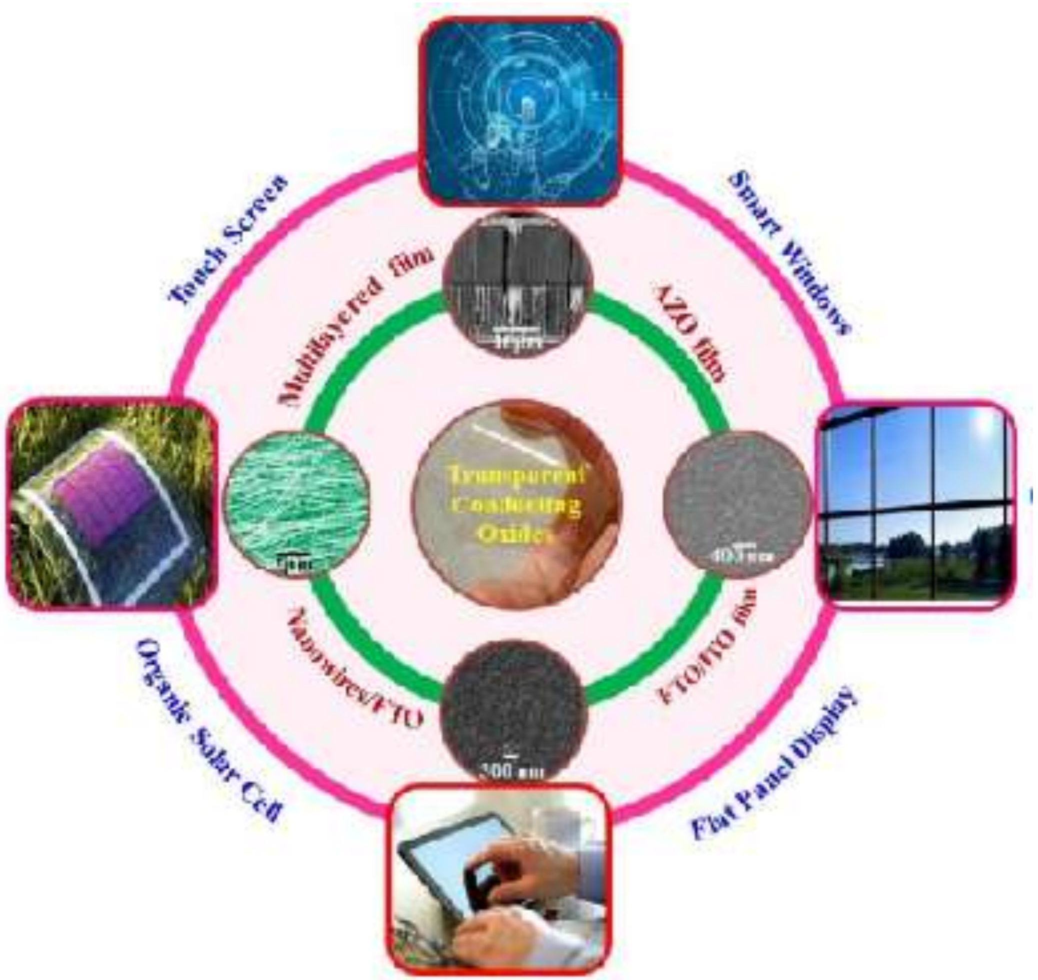
- Combine high conductivity of metals with flexibility of graphene.

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

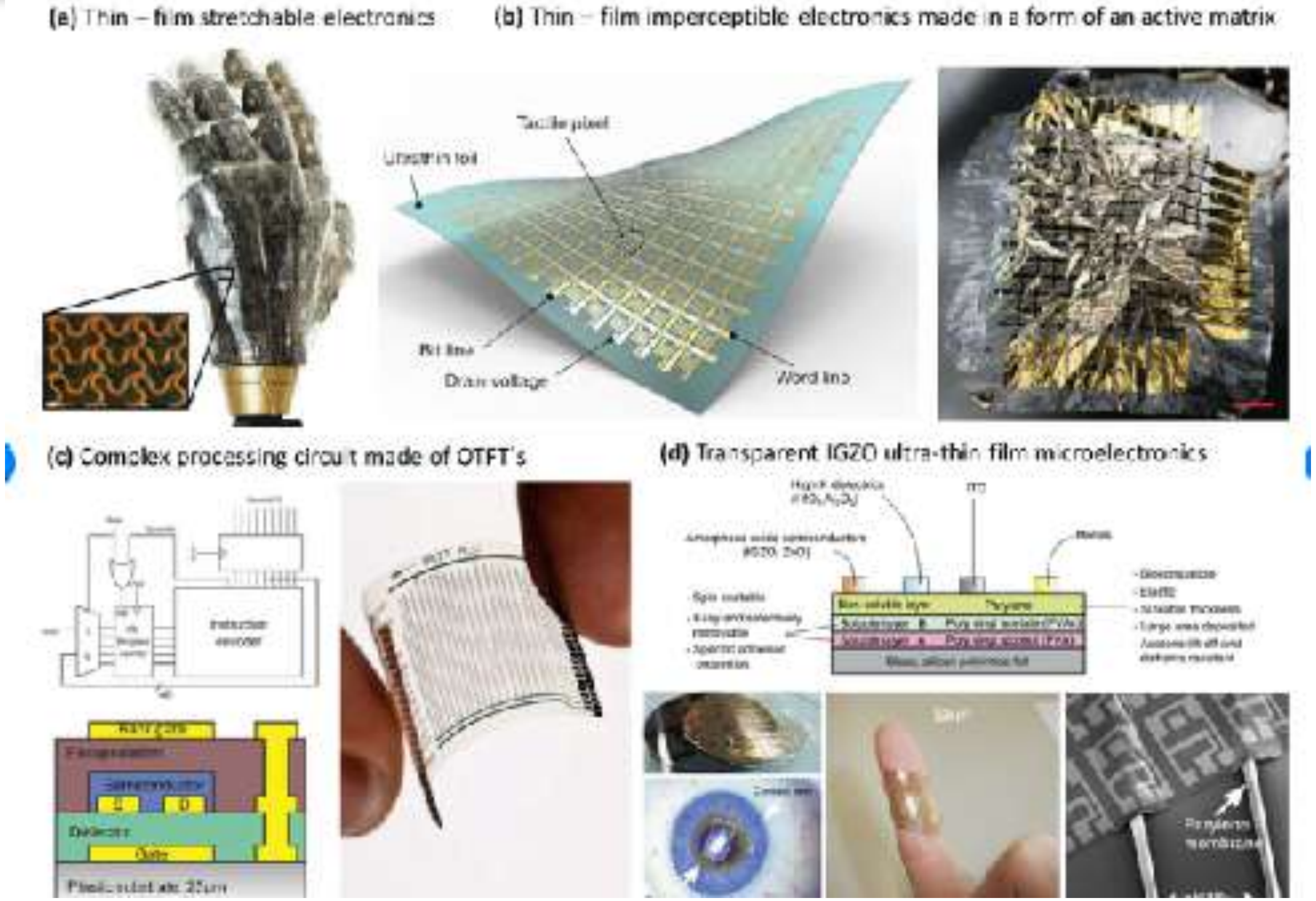
Fabrication and Reliability Concerns

- **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.