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*Chapter 6*  
*Summary and*  
*Future Scope*

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## **Summary**

ZnO, TiO<sub>2</sub>, CdS, CeO<sub>2</sub>, CuO, ZrO<sub>2</sub> as well as composites TiO<sub>2</sub>-ZrO<sub>2</sub> and Eu-doped TiO<sub>2</sub>-ZrO<sub>2</sub>, have been synthesized for their potential application in Dye-Sensitized Solar Cells (DSSCs). The hydrothermal method, which provides a controlled environment for the growth of highly pure and crystalline materials was used for synthesizing these materials. CuO was synthesized using the precipitation method.

### **Structural and Optical Properties**

The materials were characterised by X-ray diffraction (XRD) and UV-Visible spectroscopy. The X-ray diffraction (XRD) was used for studying the structural properties of these materials. The pattern confirms the formation of pure crystalline phases in almost all the materials. The average crystallite sizes, calculated using the Scherrer formula, ranged from 6.47 nm to 23.94 nm, indicating nanometre-sized formations. Hence, the materials are favourable for DSSC applications due to their higher surface to volume ratio.

The optical properties, examined using UV-Visible spectroscopy, demonstrated good absorption in the UV-Visible region with the exception of ZrO<sub>2</sub>, which exhibited absorption below 260 nm, indicating a significantly higher bandgap value. CuO displayed broad absorption across the whole spectrum without any specific peak. However, this broad absorption range can be advantageous for DSSC applications. The optical band gaps, calculated using Tauc's method, ranged from 1.35 eV (CuO) to 4.80 eV (ZrO<sub>2</sub>). The refractive index of the materials ranged from 2.03 to 3.04. this higher value of refractive index can enhance the path of light within the material, leading to more efficient photon absorption and improved solar cell performance.

### **DSSC Fabrication and Performance**

Simple and cost-effective DSSCs were fabricated using the synthesized materials. To reduce costs, the expensive Ruthenium dye used in conventional DSSC's was replaced by Anthocyanin dye extracted from pomegranate juice. The platinum counter electrode was substituted with a graphite coating, using a pencil. The layer was coated using the simple and inexpensive Doctor blade method. The barrier layers of different materials in different combinations were introduced between the electrodes to provide appropriate

gradient to electrons to reach the conducting plates. The placement of the layers was decided on the basis of their LUMO levels of the materials.

The cells were fabricated in different configurations in terms of the coated layers. The efficiency parameters of the cells were determined from their I-V characteristics.

**Single Layer Solar Cells (only active material layer):** The efficiency varied from 0.35% to 2.77%, with the highest efficiency observed for the cell prepared with TiO<sub>2</sub> (2.77%) and the lowest for CuO (0.35%).

**Two Layer Solar Cells:** In configurations with one active material and one barrier layer, the efficiency ranged from 2.07% (ZnO + ZrO<sub>2</sub>) to 5.68% (ZnO + CdS). The cells were prepared with ZnO as the active layer and four different thickness of barrier layers for each material. The optimum thickness was found to be around 12 μm, which gave the maximum efficiency in all categories.

**Three Layer Solar Cells:** For cells with one active material and two barrier layers, the combined thickness of the layers was kept at approximately 12 μm. The highest efficiency observed was 9.93% for the cell with ZnO/CdS/CuO combination, while the lowest efficiency was 4.39% for ZnO/ZrO<sub>2</sub>/CuO combination.

**Multi-Layered Solar Cells:** For cells with multiple barrier layers, the highest efficiency observed was 0.86%.

It was observed that the efficiency of DSSCs increased with the addition of barrier layers, but only up to a certain point. When the number of barrier layers increased from two to three, the efficiency decreased. This decline in power conversion efficiency is attributed to the increased thickness of multilayer structure, which can impede electron transport due to higher resistance and reduced overall performance.

## Future Scope

Incorporating recombination barrier layers is a promising strategy to enhance the performance of Dye-Sensitized Solar Cells (DSSCs). These layers can inhibit electron-hole recombination, thereby improving charge separation and electron transport. Various aspects of the barrier layer like material of layer, placement of layers, thickness of layers, deposition of layers, choice of dye and fabrication of cells offer a vast array of possibilities to be explored.

- Apart from the materials used for this study, materials like  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$  and  $\text{MgO}$ , although with higher band gap values but appropriate LUMO levels can be explored as either the photoanode or barrier layer.
- Additionally, composites other than the one used in the study e.g.  $\text{TiO}_2\text{-CeO}_2$ ,  $\text{CeO}_2\text{-ZrO}_2$ , etc can be synthesized and explored as photoanode materials. There is an extensive choice of dopants in transition as well as rare earth metals to manipulate the photoconductivity of the materials.
- The choice of these single materials as well as composites throw a substantial challenge in the placement of layers, as strategic placement requires the matching of LUMO levels. Hence, combinations are open for studies.
- Thickness of the layers is one of the most crucial parameters, as it determines the resistive path of the flow of electrons. The control over thickness is a function of the precision of the deposition technique. Spin coating and Chemical vapour deposition are better options among the low-cost alternatives for exploring.
- Another important aspect of this work is the use of fruit extract as dye, replacing the conventional chemical dye. This is extremely important from the point of view of environment and offers a range of plant-based options to be studied for sustained performance of the cells.
- The fabrication process and its precision also matter as it has a role to play in determining the series and shunt resistance of the units.

Thus, the vast array of options provided in each of the above aspects offer a substantial scope for different permutations and combinations to be studied in future.