Fabrication of Copper–Indium Selenide (CIS) Thin Films and Their Importance in Photovoltaic Applications

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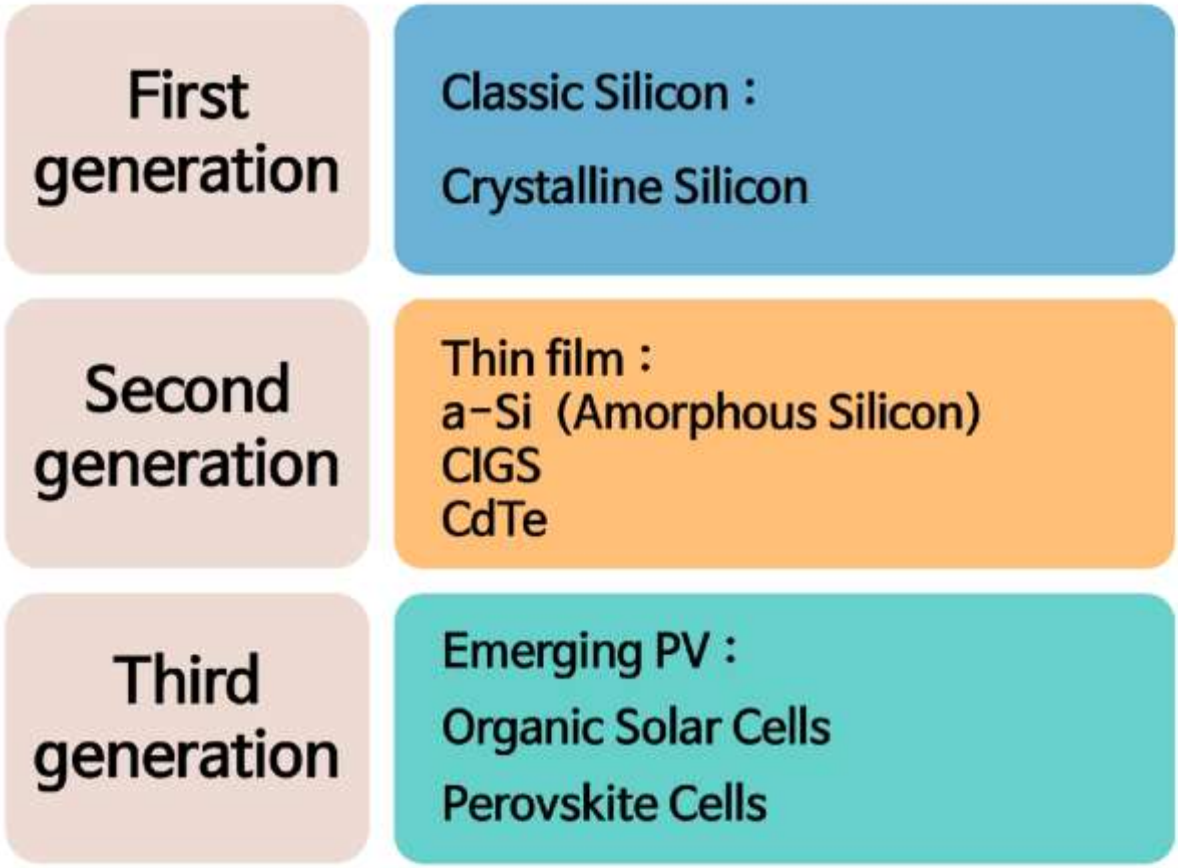
Abstract: Copper–indium selenide ($CuInSe_2$ or CIS) is a I–III–VI_2 compound semiconductor widely studied for thin-film photovoltaic applications due to its high absorption coefficient, suitable direct band gap, and excellent long-term stability. CIS-based solar cells, including Cu(In,Ga)Se_2 (CIGS), have achieved some of the highest efficiencies among thin-film technologies. This paper reviews the fundamental properties of CIS, various fabrication techniques, and the technological importance of CIS in renewable energy systems. Emphasis is placed on deposition methods such as co-evaporation, sputtering followed by selenization, electrodeposition, and non-vacuum processes. The importance of CIS in terms of efficiency, cost-effectiveness, flexibility, and sustainability is also discussed.

Keywords: Copper–indium selenide, CIS thin films, fabrication techniques, photovoltaic materials, solar cells

Introduction : The growing demand for sustainable and renewable energy sources has accelerated research into high-efficiency photovoltaic (PV) materials. Thin-film solar cells have gained significant attention due to their low material consumption and potential for low-cost manufacturing. Among these materials, copper–indium selenide (CIS) has emerged as a promising absorber layer owing to its excellent optoelectronic properties.
CIS is a direct band-gap semiconductor with a band gap of approximately 1.0 eV, which is close to the optimum value for solar energy conversion. Its ability to absorb sunlight efficiently

even in very thin layers makes it highly suitable for next-generation solar technologies.

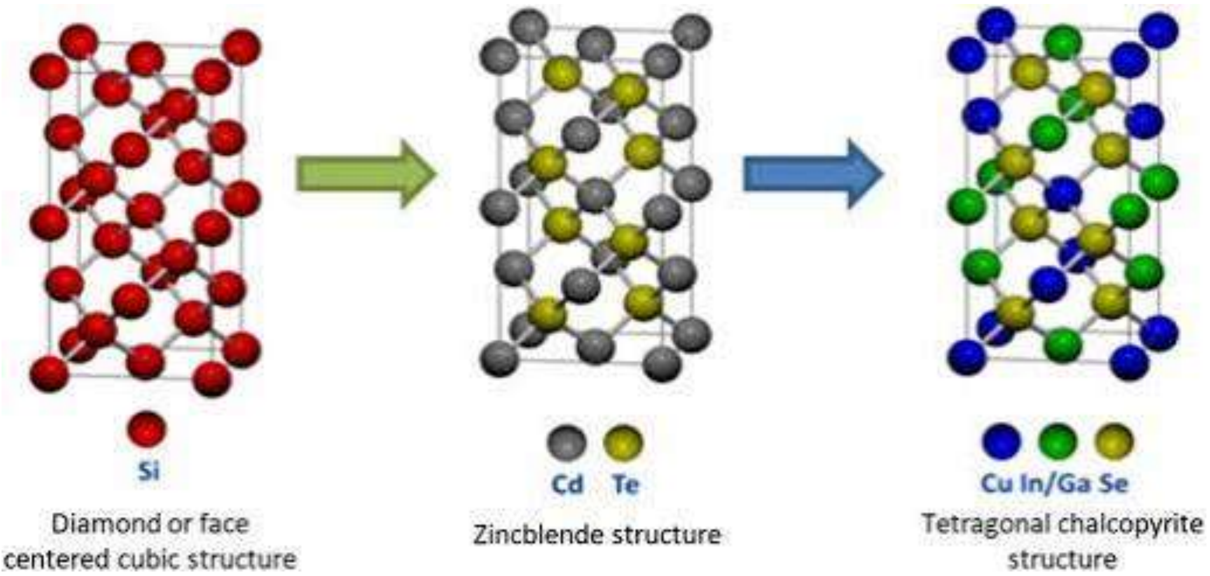


Material Properties of Copper–Indium Selenide : The thermochemistry of the Cu–In–Se ter-nary material system has been studied intensely, but significant inconsistencies abound and the incompleteness of the extant scientific literature will become apparent to the reader. One superfi- cial inconsistency is in the Greek letter designa- tions employed to describe the various phases, but even today there persist more substantive dis- agreements, for example, on the number of phases found in the ternary phase field. To avoid confu- sion all discussions herein that employ Greek letter designations to identify thermodynamic of phases will use the identifiers from the work

Boehnke and Kühn.23 Experimental studies that require bulk syn- thesis are extraordinarily difficult because of the high vapor pressure of selenium and reactivity of copper with quartz ampoules typically used.24 Therefore, it is difficult to ensure that the thermo- dynamic system remains closed during synthesis and that the resulting constitution accurately re- flects the starting material ratios. Thus, it is diffi- cult to judge whether syntheses intended to lie on the Cu2Se – In2Se3 pseudobinary section remain so, hence whether that section is actually an equi- librium tie-line. Although considerable progress has been made in the bulk synthesis of these compounds,9 uncertainties such as these persist to this day in efforts to assess the phase diagram. The earliest published study of the Cu–In–Se phase25 was restricted to a segment of the presum- ably pseudobinary section between the compounds Cu2Se and In2Se3, and centered on the equimolar composition corresponding to CuInSe2. Several key features of Palatnik and Rogacheva's results have been confirmed in subsequent studies of this system, albeit with different values of the critical point temperature and compositions. First, con- gruent melting of the solid compound with a com- position near that of CuInSe2 at a

temperature somewhat less than 1000°C (986°C) is observed. Second, a congruent first-order solid-solid (α to δ) phase transition at a lower temperature (810°C) of that high-temperature phase *via* a crystallo- graphic order-disorder transition between the cat- ion-disordered sphalerite structure (δ phase) and the chalcopyrite structure (α phase) is observed.
Third, temperature-dependent extensions of the phase homogeneity range of the chalcopyrite struc- ture to somewhat indium-rich compositions, but none toward copper-enrichment are observed. Fourth, peritectoid decomposition of the sphaler- ite phase at its lowest stable temperature into the chalcopyrite and a relatively indium-rich defect- tetragonal structure is observed. Copper–indium selenide crystallizes in a chalcopyrite crystal structure and exhibits strong p-type conductivity. Some key properties include:

1. High absorption coefficient (>10^5 cm^{-1}), enabling effective absorption of solar radiation with films only a few micrometers thick
2. Direct band gap (~1.0 eV), ideal for photovoltaic energy conversion
3. High radiation and thermal stability, suitable for long-term outdoor operation
Tolerance to defects, allowing high performance even in polycrystalline form
These properties make CIS superior to many conventional semiconductor materials used in thin-film solar cells.



Fabrication Techniques of CIS Thin Films : The performance of CIS solar cells strongly depends on the fabrication technique used. Several deposition and synthesis methods have been developed to optimize film quality, stoichiometry, and scalability.

1. Co-Evaporation Technique

Co-evaporation is the most widely used and highest-efficiency fabrication method for CIS and CIGS thin films. In this process, copper, indium, and selenium are simultaneously evaporated onto a heated substrate under vacuum conditions. Multi-stage co-evaporation allows precise control of composition and grain growth, leading to high-quality absorber layers.
This technique has produced record-efficiency CIS-based solar cells but requires complex vacuum systems and high capital investment.

2. Sputtering Followed by Selenization

In this method, metallic layers of copper and indium are first deposited by sputtering at low temperature. The precursor film is then annealed in a selenium atmosphere to form CIS.
Advantages include:

- Better uniformity over large areas
- Higher throughput compared to co-evaporation
- Suitability for industrial-scale production

However, precise control of the selenization process is essential to avoid secondary phase formation.

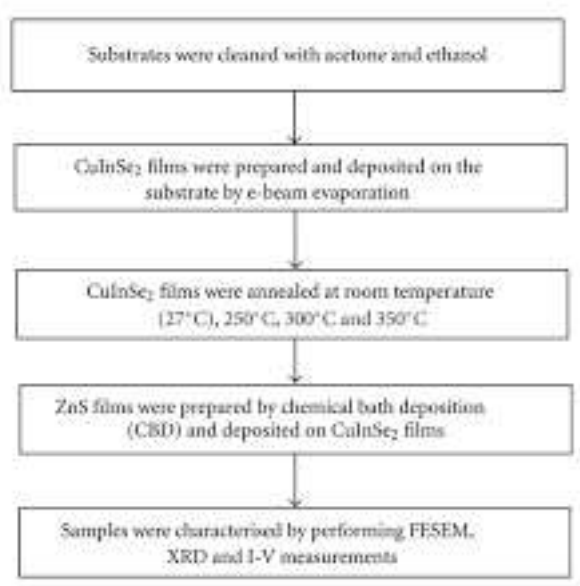
3. Electrodeposition

Electrodeposition is a low-cost, non-vacuum technique in which Cu, In, and Se ions are deposited from an electrolyte solution onto a conductive substrate. Subsequent annealing converts the deposited layer into crystalline CIS.
This method is attractive for large-scale manufacturing due to its low energy consumption and material efficiency, although device efficiencies are generally lower than those achieved with vacuum-based techniques.

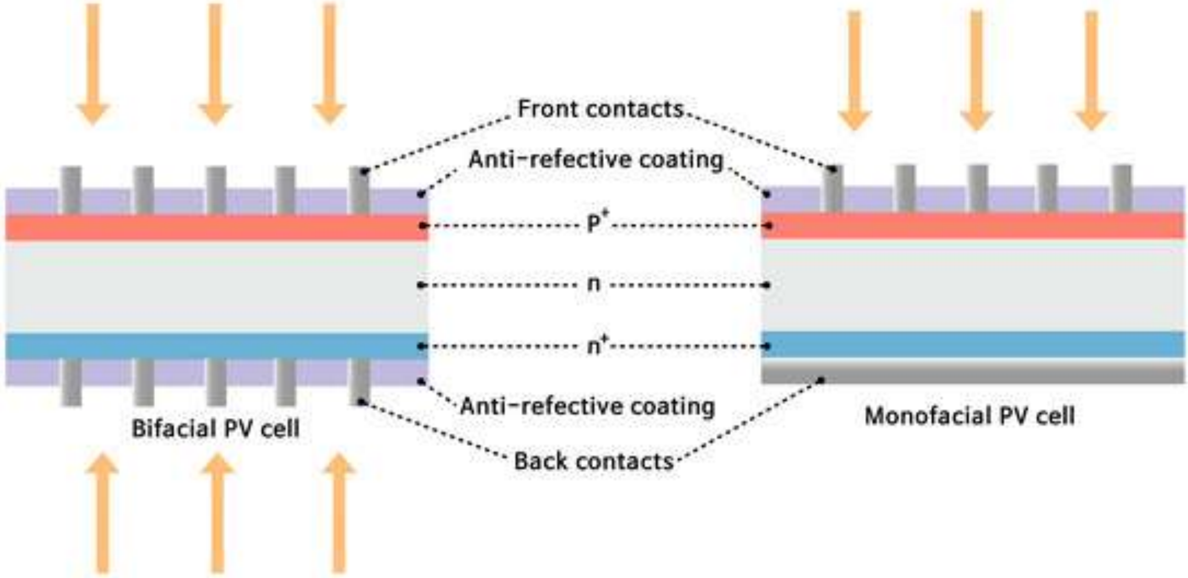
Solution-processed CIS fabrication involves depositing nanoparticle inks or metal-oxide precursors followed by high-temperature selenization. These methods offer advantages such as:

- Reduced manufacturing cost
- Roll-to-roll compatibility
- Minimal material waste

Despite these benefits, challenges remain in achieving uniform grain growth and high conversion efficiencies.



Importance of Copper–Indium Selenide



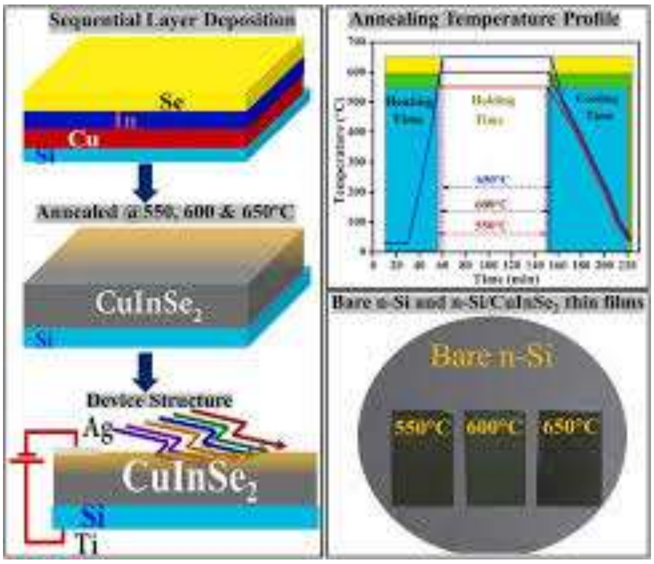
1. ***High Photovoltaic Efficiency :*** CIS and CIGS solar cells have demonstrated efficiencies exceeding 20%, making them among the most efficient thin-film photovoltaic technologies available today.

2. ***Cost-Effective Solar Technology:*** Due to the thin absorber layer and compatibility with low-cost substrates such as glass and flexible polymers, CIS-based solar cells offer significant cost advantages over crystalline silicon technologies. This supports large-scale deployment and energy affordability.

3. ***Flexible and Lightweight Applications:*** CIS thin films can be deposited on flexible substrates, enabling applications in:

- Building-integrated photovoltaics (BIPV)
- Portable power systems
- Space and aerospace technologie

4. ***Environmental and Energy Sustainability:*** CIS solar cells require less energy for fabrication and have a shorter energy payback time compared to silicon solar cells. Their long operational lifetime further enhances their sustainability profile.s



5. **Challenges and Future Prospects:** copper Indium Selenide ($CuInSe_2$, CIS) is a key absorber material for thin-film photovoltaic (PV) technologies due to its high absorption coefficient, tunable band gap, and excellent radiation stability. Despite these advantages, several technical, economic, and environmental challenges must be addressed to enable its large-scale commercialization. At the same time, ongoing research presents promising future prospects for CIS-based

1. Challenges of Copper Indium Selenide

1.1 Material Scarcity and Cost: Indium is a rare and expensive element, primarily obtained as a by-product of zinc mining. Limited global reserves raise concerns about long-term sustainability and supply chain stability. High material cost affects the economic competitiveness of CIS solar cells compared to silicon and emerging perovskite technologies.

1.2 Stoichiometric Control and Defect Chemistry : CIS has a narrow phase stability region, making precise control of Cu/In/Se ratios difficult.
Deviations lead to secondary phases such as:

- Cu_2Se (conductive shunting paths)
- In_2Se_3 (reduced carrier concentration)
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Native defects (vacancies and antisite defects) strongly influence electrical properties and device performance.

1.3 Fabrication Complexity: High-efficiency CIS devices often require high-temperature, multi-step deposition processes, such as:

- Co-evaporation
- Selenization of metal precursors
- These processes increase:

- Equipment cost
- Energy consumption
- Reproducibility challenges in large-area modules

1.4 Interface and Stability Issues : Performance is sensitive to interfaces, particularly between CIS and buffer layers (e.g., CdS). Interfacial recombination can reduce:

- Open-circuit voltage (Voc)
- Fill factor (FF)
- Long-term stability can be affected by:
- Moisture ingress
- Thermal cycling
- Elemental diffusion at interfaces

1.5 Environmental and Health Concerns

Use of selenium and cadmium (in CdS buffer layers) raises toxicity concerns.
Disposal and recycling of CIS modules require strict environmental management.
Compliance with environmental regulations can increase production costs.

2. Future Prospects of Copper Indium Selenide

2.1 Material Engineering and Alloying Partial substitution of indium with gallium (forming CIGS) allows:

- Band gap tuning (1.0–1.7 eV)
- Higher power conversion efficiencies
- Defect engineering and alkali metal doping (Na, K, Rb) improve:
- Grain growth
- Carrier lifetime
- Device efficiency

2.2 Advanced Low-Cost Fabrication Techniques

Development of solution-based and low-temperature processes, such as:

- Nanoparticle inks
- Electrodeposition
- Spray pyrolysis
- These methods enable:
- Reduced manufacturing costs
- Roll-to-roll and flexible substrate applications

2.3 Tandem and Multi-Junction Solar Cells
CIS is a promising candidate for tandem solar cells, especially when combined with:

- Perovskites
- Silicon

Its tunable band gap and high absorption make it suitable for bottom-cell absorber layers.

2.4 Space and Harsh-Environment Applications

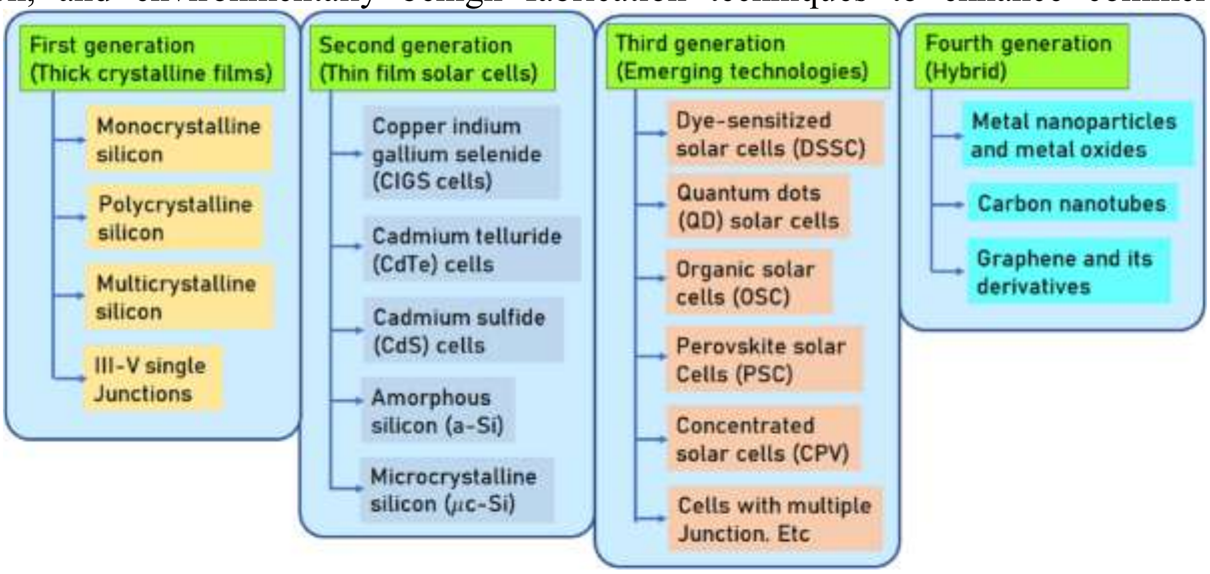
CIS exhibits excellent:
Radiation hardness
Temperature stability
These properties make it ideal for:
Space photovoltaics
Military and remote power systems

2.5 Recycling and Sustainability Research
Research into indium recovery and recycling from end-of-life modules is growing. Development of cadmium-free buffer layers (e.g., Zn(O,S), In_2S_3) reduces environmental impact. Life-cycle assessment (LCA) studies support CIS as a low-carbon energy technology.

Despite its advantages, CIS technology faces challenges such as:

- Indium scarcity and cost
- Complex fabrication control
- Scale-up limitations for non-vacuum processes

Future research focuses on material optimization, indium reduction, tandem solar cell integration, and environmentally benign fabrication techniques to enhance commercial



viability.

Conclusion: Copper–indium selenide is a highly promising material for thin-film photovoltaic applications due to its excellent optoelectronic properties, high efficiency, and adaptability to flexible substrates. Advances in fabrication techniques continue to improve performance and reduce production costs. With ongoing research and technological development, CIS-based solar cells are expected to play a vital role in the global transition to renewable energy. While Copper Indium Selenide faces challenges related to material scarcity, fabrication complexity, and environmental concerns, continuous advancements in material engineering, deposition techniques, and device architecture present strong future prospects. With improvements in sustainability and cost-effectiveness, CIS and related CIGS technologies are expected to remain important contributors to next-generation thin-film photovoltaic systems.

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