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Thin-film solar photovoltaic technologies: materials, device structures, and engineering challenges

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ABSTRACT

Thin-film photovoltaic (PV) technologies offer an alternative to conventional crystalline-silicon solar cells through the use of thin semiconductor layers deposited on glass, metal, or flexible substrates. Their principal advantages include reduced semiconductor-material consumption, potentially lower manufacturing costs, and compatibility with large-area and lightweight applications. The most established thin-film technologies include amorphous and microcrystalline silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), while kesterite compounds such as copper zinc tin sulfide (CZTS) and emerging perovskite absorbers represent additional research directions. Despite significant progress in laboratory efficiency and commercial production, thin-film PV technologies face challenges related to material availability, toxicity, interface defects, long-term stability, and manufacturing uniformity. This review discusses the principal absorber materials, device structures, performance developments, and engineering challenges reported through 2014. It argues that the future competitiveness of thin-film PV depends not only on improving conversion efficiency but also on achieving reliable, scalable, and environmentally responsible manufacturing.

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1. INTRODUCTION

Thin-film solar photovoltaic technologies have developed as an important alternative to wafer-based crystalline-silicon solar cells. Instead of relying on relatively thick semiconductor wafers, these technologies use thin absorber layers deposited onto supporting substrates, reducing material consumption and enabling different device configurations. Their potential advantages include lightweight construction, flexible form factors, and compatibility with large-area manufacturing processes [1], [2].

The term thin-film PV covers several material systems with different optical, electrical, and manufacturing characteristics. The principal commercial technologies are amorphous-silicon (a-Si:H), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), while copper zinc tin sulfide (CZTS) and organic–inorganic halide perovskites were attracting growing research interest by 2014 [2]–[5]. This review examines these technologies, emphasizing their materials, device architectures, performance, and engineering limitations based exclusively on literature published no later than 2014.

2. MATERIALS AND DEVICE STRUCTURES

2.1. Amorphous and microcrystalline silicon

Hydrogenated amorphous silicon (a-Si:H) is a non-crystalline semiconductor that absorbs sunlight efficiently in relatively thin layers. Its ability to be deposited over large areas at comparatively low temperatures makes it suitable for glass and flexible substrates. However, a-Si:H devices generally exhibit lower conversion efficiency than leading CdTe and CIGS cells, and their performance can decline under prolonged illumination because of the Staebler–Wronski effect [1], [2].

A typical a-Si:H solar cell uses a p-i-n structure in which an intrinsic absorber layer is positioned between p-type and n-type doped layers. The intrinsic layer absorbs incoming photons, while the doped layers establish the electric field needed to separate and collect photogenerated charge carriers. Tandem and triple-junction structures combine absorbers with different optical gaps to improve sunlight utilization and reduce some of the limitations of single-junction devices [2], [6].

Microcrystalline silicon (μc-Si:H) can complement a-Si:H because it absorbs longer-wavelength light more effectively. Combining amorphous and microcrystalline silicon in a micromorph tandem structure broadens the spectral response and can improve performance compared with a single a-Si:H junction. Nevertheless, light trapping, deposition throughput, and long-term stability remain important engineering considerations [2], [6].

2.2. Cadmium telluride (CdTe)

CdTe is a direct-bandgap semiconductor with a high optical absorption coefficient, allowing most incident sunlight to be absorbed in a relatively thin layer. Its near-optimal bandgap for single-junction solar conversion and compatibility with large-area deposition have made it one of the most commercially established thin-film PV technologies. The principal concern is the use of cadmium, which requires careful control of occupational exposure, manufacturing emissions, and end-of-life recycling [2], [7].

A conventional CdTe device commonly uses a superstrate configuration, with glass as the front support and transparent conducting oxide as the front electrical contact. A cadmium sulfide (CdS) buffer layer forms a heterojunction with the CdTe absorber, while a rear contact completes the device. The absorber is typically deposited by processes such as close-spaced sublimation or other vapor-based techniques, followed by thermal treatment and contact formation [7].

2.3. Copper indium gallium selenide (CIGS)

CIGS is a direct-bandgap chalcopyrite semiconductor whose optical properties can be adjusted by changing the relative gallium and indium composition. Its strong absorption enables thin absorber layers, while its composition flexibility allows the bandgap to be tuned for improved device performance. CIGS devices have achieved high laboratory efficiencies, although manufacturing complexity and the availability of indium and gallium remain important concerns [2], [8].

A typical CIGS cell is built in a substrate configuration, often using soda-lime glass, a molybdenum rear contact, the CIGS absorber, a thin CdS buffer, and a transparent conducting oxide window layer. The absorber can be produced through co-evaporation or through precursor deposition followed by selenization. The composition and distribution of gallium, alkali elements, and defects strongly influence carrier collection and device performance [8].

2.4. Copper zinc tin sulfide (CZTS)

CZTS and its selenium-containing counterpart, CZTSSe, have attracted attention because they use comparatively abundant elements such as copper, zinc, tin, sulfur, and selenium. These materials offer a possible route to reduce dependence on scarce or expensive elements used in some established thin-film technologies. However, their performance has been limited by defects, secondary phases, and difficulties in controlling composition during synthesis [4], [9].

CZTS-based devices generally adopt a substrate architecture similar to that used for CIGS, with a molybdenum back contact, absorber layer, buffer layer, and transparent front contact. Their potential sustainability advantage is significant, but further improvements in absorber quality, interface control, and reproducible large-area processing are necessary before they can compete with mature thin-film technologies [9].

2.5. Emerging perovskite thin-film solar cells

Organic–inorganic halide perovskites emerged rapidly as promising thin-film absorbers in the period immediately preceding 2014. These materials combine strong visible-light absorption with favorable charge-transport properties and can be deposited using relatively low-temperature solution-processing methods. Their rapid efficiency improvement made them a notable research direction, although long-term stability and the presence of lead raised important concerns [5], [10].

Perovskite devices had been demonstrated in mesoscopic and planar architectures by 2014. In mesoscopic structures, a porous electron-transport scaffold supports the perovskite absorber, whereas planar devices use compact charge-selective layers around the absorber. The rapid progress in this field was accompanied by unresolved questions about moisture sensitivity, thermal stability, hysteresis, and scalable encapsulation [5], [10].

3. PERFORMANCE AND TECHNOLOGY COMPARISON

Thin-film technologies differ considerably in their laboratory performance, commercial maturity, and manufacturing requirements. By 2014, CdTe and CIGS had demonstrated the strongest efficiencies among the major commercial thin-film absorber technologies, while a-Si:H generally achieved lower efficiencies but offered mature large-area deposition and established applications. CZTS and perovskites showed substantial research potential, although their long-term reliability and production scalability were not yet established [3], [5], [8], [9]. Table 1 presents a comparative overview of the major thin-film photovoltaic technologies, highlighting their absorber materials, typical device structures, main advantages, and key limitations.

Table 1. Comparison of major thin-film photovoltaic technologies

Technology	Absorber material	Typical device structure	Main advantages	Main limitations
a-Si:H	Hydrogenated amorphous silicon	Glass/TCO/p-i-n/TCO	Low material use; large-area deposition; flexible substrates possible	Light-induced degradation; relatively low efficiency
μc-Si:H	Microcrystalline silicon	Glass/TCO/p-i-n/TCO	Better long-wavelength absorption than a-Si:H; tandem compatibility	Deposition time; light-management requirements
CdTe	Cadmium telluride	Glass/TCO/CdS/CdTe/back contact	High absorption; suitable bandgap; established manufacturing	Cadmium toxicity; tellurium supply and recycling
CIGS	Copper indium gallium selenide	Glass/Mo/CIGS/buffer/TCO	High efficiency; adjustable bandgap; strong absorption	Indium and gallium availability; process complexity
CZTS/CZTSSe	Copper zinc tin sulfide/selenide	Glass/Mo/CZTSSe/buffer/TCO	More abundant constituent elements; strong absorption	Phase control; defects; lower demonstrated efficiency
Perovskite	Organic–inorganic metal halide	Planar or mesoscopic transport-layer/absorber structure	Rapid efficiency improvement; low-temperature processing potential	Moisture and thermal instability; lead content; scale-up uncertainty

Note: TCO = transparent conducting oxide; Mo = molybdenum; p-i-n = p-type/intrinsic/n-type structure. Architectures are representative rather than universal.

The efficiency records reported in the 2014 edition of the solar cell efficiency tables provide a useful snapshot of the progress achieved by the end of the review period. The reported values refer to independently confirmed research cells and should not be interpreted as typical commercial module efficiencies. Differences in cell area, test conditions, and device configuration also mean that the figures are not a direct measure of manufacturing cost or field performance [10]. Table 2 summarizes the selected thin-film research-cell efficiency records reported by 2014, providing a comparison of the highest recorded efficiencies across different technologies and their respective reference periods.

Table 2. Selected thin-film research-cell efficiencies reported by 2014

Technology	Reported cell efficiency	Reference period/record context
CIGS	20.5%	2014 efficiency tables; record reported in 2014
CdTe	20.4%	2014 efficiency tables; record reported in 2013
Perovskite	17.9%	2014 efficiency tables; record reported in April 2014
CZTSSe	12.6%	2014 efficiency tables; record reported in 2013
Amorphous silicon	10.1%	2014 efficiency tables; stabilized cell record
CZTS	8.5%	2014 efficiency tables; record reported in 2013

Source: "Solar cell efficiency tables (version 44)," published in 2014. Values are research-cell records, not commercial module ratings.

4. ENGINEERING CHALLENGES

4.1. Material quality and defect control

Material quality is a central factor determining the performance of thin-film solar cells. Grain boundaries, vacancies, impurities, secondary phases, and non-uniform elemental composition can introduce recombination pathways that reduce voltage and charge-carrier collection. These issues are particularly important in multicomponent absorbers such as CIGS and CZTS, where small changes in composition or processing conditions can significantly affect the resulting electronic properties [8], [9].

4.2. Deposition and manufacturing scalability

A second major challenge is translating laboratory fabrication processes into reproducible industrial production. Vacuum-based techniques such as co-evaporation and sputtering can provide good control over film composition, but equipment cost, throughput, and process uniformity must be managed. Solution-based and other non-vacuum approaches may reduce equipment requirements, although controlling crystallinity, stoichiometry, porosity, and large-area uniformity remains difficult [9].

4.3. Interface engineering and electrical contacts

The interfaces between absorber, buffer, and window layers strongly influence carrier separation, recombination, and electrical resistance. Poor band alignment, interfacial defects, and non-ideal contacts can limit device performance even when the absorber itself has good optical properties. Consequently, buffer-layer selection, surface treatment, contact formation, and transparent-electrode optimization are essential parts of thin-film device engineering [2], [7], [8].

4.4. Stability and environmental considerations

Long-term stability is essential for the commercial viability of thin-film PV modules. Exposure to moisture, oxygen, heat, ultraviolet radiation, and mechanical stress can cause degradation in materials, interfaces, and encapsulation systems. Environmental considerations also differ by technology: CdTe requires responsible cadmium management and recycling, CIGS relies partly on elements with supply constraints, and lead-containing perovskites raise concerns about toxicity and leakage during operation or disposal [5], [7], [8], [10].

4.5. Module integration and reliability

High laboratory cell efficiency does not automatically translate into high module performance or low lifetime energy cost. Large-area modules require reliable interconnection, uniform deposition, effective encapsulation, and resistance to environmental and mechanical stresses. Manufacturing yield, degradation rate, repairability, and end-of-life management therefore need to be considered alongside conversion efficiency when comparing thin-film technologies [2], [3].

5. DISCUSSION AND FUTURE PERSPECTIVES

The comparison of thin-film PV technologies indicates that no single absorber material simultaneously provides high efficiency, low cost, abundant resources, environmental safety, and mature manufacturing. CdTe and CIGS had achieved strong performance and commercial deployment by 2014, but their materials supply and environmental profiles require continued attention. Amorphous silicon remains relevant for applications where low weight, transparency, or flexible form factors are more important than maximum conversion efficiency [2], [3].

Emerging materials may address some of the limitations of established technologies, but their advantages must be assessed against practical engineering requirements. CZTS offers a promising route based on more abundant elements, yet defects and phase control remain major obstacles to performance improvement [9]. Perovskites demonstrated exceptionally rapid efficiency gains by 2014, but stability, lead management, and scalable encapsulation were still unresolved challenges [5], [10].

Future development should therefore combine absorber-material innovation with improvements in deposition control, interface engineering, module design, and reliability testing. Research priorities should include reducing non-radiative recombination, improving large-area uniformity, developing durable encapsulation, and evaluating environmental impacts across the complete product life cycle. A balanced assessment based on efficiency, lifetime energy yield, material availability, manufacturing cost, and recyclability will provide a more realistic basis for selecting thin-film PV technologies.

6. CONCLUSION

Thin-film photovoltaic technologies provide a diverse set of alternatives to conventional crystalline-silicon solar cells through their reduced absorber thickness, flexible device architectures, and potential for large-area manufacturing. Their ability to use less semiconductor material and support different substrate configurations make them attractive for applications requiring lightweight, flexible, or building-integrated solar modules. CdTe, CIGS, and thin-film silicon represented the most established technologies by 2014, while CZTS and perovskite materials offered promising research opportunities due to their distinctive material properties and potential for further efficiency improvements. Despite these advantages, their continued development depends on overcoming challenges in material quality, deposition scalability, interface control, operational stability, and environmental management. Further research is needed to

improve manufacturing consistency, minimize defects, enhance module durability, and reduce dependence on scarce or potentially hazardous elements. Ultimately, commercial success will require not only high conversion efficiency but also reliable modules, sustainable material use, cost-effective production, and competitive lifetime performance.

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