

EMERGING SOLAR CELL TECHNOLOGIES: ADVANCEMENTS AND CHALLENGES IN PERFORMANCE: A REVIEW

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Abstract

Solar photovoltaic (PV) technology is a key component of renewable energy systems, enabling the direct and sustainable conversion of sunlight into electricity. Over recent decades, PV technologies have evolved from conventional silicon-based devices to advanced thin-film technologies such as CIGS and CdTe, offering benefits in cost, flexibility, and lightweight design. Recent improvements in power conversion efficiency and solution-processable fabrication have positioned perovskite solar cells as highly promising. Emerging materials, including organic semiconductors and quantum dots, are also being explored. This review examines PV operating principles, material classifications, performance metrics, and key challenges, while highlighting future research directions such as tandem architectures and hybrid materials [1][2][3].

Introduction

Due to its minimal environmental impact, solar energy has emerged as a key component of global renewable energy strategies [4][5]. Unlike fossil fuels, sunlight is abundant and virtually inexhaustible, making it an attractive solution for meeting the world's growing energy demands. The field of photovoltaic (PV) technology began with the development of the first practical silicon-based solar cell at Bell Laboratories in 1954, achieving an efficiency of approximately 6% [6]. This breakthrough demonstrated the feasibility of directly converting sunlight into electricity and stimulated decades of research focused on improving efficiency, reducing costs, and exploring new material systems [7][8].

Since then, PV technologies have advanced significantly in both device architecture and materials. Crystalline silicon (c-Si) remains the dominant commercial technology due to its high efficiency, long operational lifetime, and mature manufacturing processes. However, as silicon-based cells approach their single-junction efficiency limits, research has increasingly shifted toward advanced designs and alternative materials [9]. Thin-film solar cells—including amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe)—offer advantages such as reduced material usage, lightweight structures, and compatibility with flexible and building-integrated photovoltaic (BIPV) applications [10][11]. More recently, perovskite solar cells have emerged as a transformative technology, with power conversion efficiencies rising from below 4% to over 25% within a decade. Their tunable optoelectronic properties and solution-processable fabrication make them highly promising for next-generation devices [12]. In parallel, organic photovoltaic and quantum dot solar cells are being explored for

flexible, low-cost, and portable energy-harvesting applications.

Principles of Solar Cells

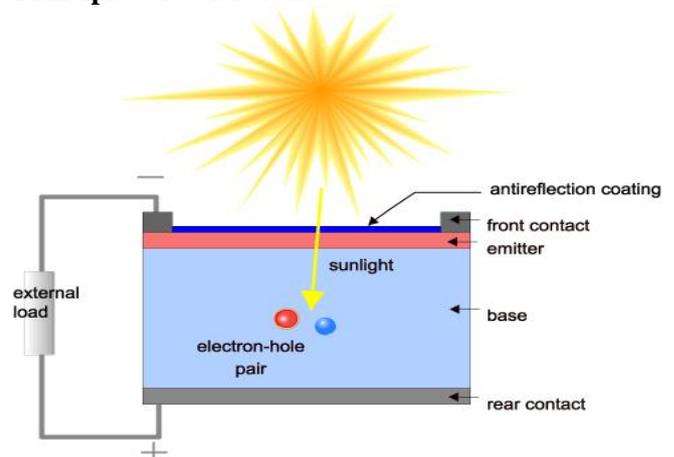


Fig.1 Construction and working of Solar Cell

Solar cells generate electricity through the photovoltaic effect, in which photons from sunlight excite electrons within a semiconductor material. When a photon with sufficient energy is absorbed, an electron is promoted from the valence band to the conduction band, creating an electron-hole pair. These charge carriers are separated by the internal electric field of the p-n junction, directing electrons toward the n-type region and holes toward the p-type region. The resulting charge flow through an external circuit produces electrical power [13][14][15]. Solar cell performance is evaluated using parameters such as short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE) [16][17].

Solar Cell Technologies

➤ Crystalline Silicon Solar Cells

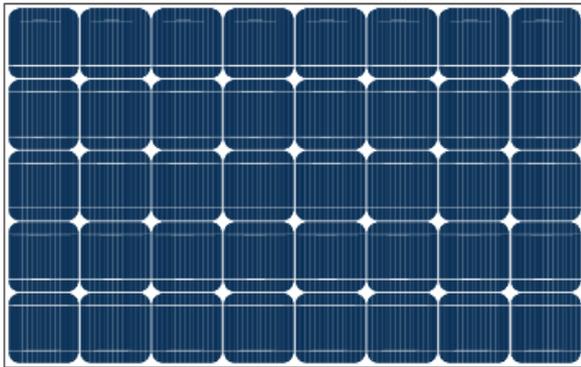


Fig. 2 Structure of Silicon Solar Cell

Crystalline silicon (c-Si) continues to dominate commercial solar cell technology due to its exceptional stability, abundance, and well-established manufacturing processes [18][19]. Monocrystalline silicon cells, fabricated from a single continuous crystal, achieve high power conversion efficiencies of up to 25% owing to minimal defects, reduced recombination, and efficient charge transport. Polycrystalline silicon cells, composed of multiple smaller crystals separated by grain boundaries, are less efficient but more cost-effective, making them suitable for large-scale installations [20][21]. To overcome these limitations, research increasingly focuses on heterojunction and tandem architectures, integrating materials with differing bandgaps and advanced optical design to enhance efficiency while maintaining the affordability and long-term reliability that make silicon the industry standard [22][23].

Thin-Film Solar Cells

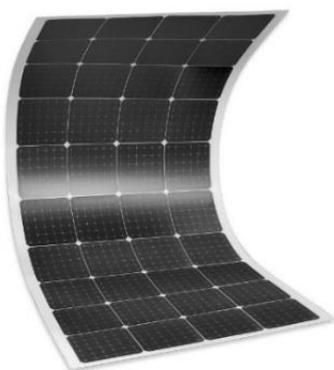


Fig. 3. Structure of Thin-Film Solar Cells

Compared to traditional crystalline silicon cells, thin-film solar cells are a significant family of photovoltaic devices that use substantially less semiconductor material. Thin-film cells achieve

reduced weight, mechanical flexibility, and material costs by depositing incredibly thin layers—typically only a few micrometers thick—onto substrates like glass, metal, or flexible polymers [24][25]. Because of these characteristics, they are especially well suited for applications requiring lightweight or flexible energy generation, portable solar devices, and building-integrated photovoltaics (BIPV).

Many thin-film technologies have been developed, each with special advantages and disadvantages: One of the most developed thin-film technologies is cadmium telluride (CdTe), which can achieve efficiencies of up to about 20% in commercial modules. It is appealing for widespread deployment because to its high absorption coefficient and low production cost. However, the presence of hazardous cadmium in the material causes environmental problems during manufacturing and disposal, which requires careful management [26][27].

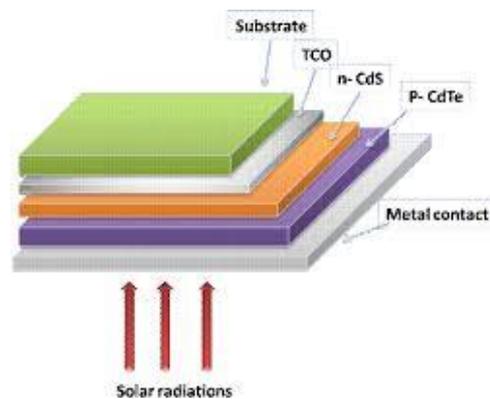


Fig. 4. Structure of cadmium telluride thin film solar cell

Compared to single-junction silicon, Copper Indium Gallium Selenide (CIGS) cells have a configurable band gap that makes better use of the sun spectrum. They attain intermediate efficiency (~22%) and are mechanically flexible, allowing deposition on lightweight or curved surfaces. Because of its tunability, CIGS is also a good option for tandem solar cell designs, which combine several layers with various band gaps to optimize energy capture [28, 29]. Amorphous Silicon (a-Si): The disorganized atomic structure of a-Si cells restricts the mobility of charge carriers and lowers efficiency to about 10%. Despite this, a-Si is highly adaptable, useful for flexible substrates and semitransparent devices. Integration into windows, electronics, and portable solar panels is made possible by its capacity to be deposited on low-temperature substrates [30]. Thin-film solar cells are especially useful for uses outside of traditional rooftops because they combine lightweight design, flexibility, and material efficiency. Their integration into BIPV systems—

such as facades, skylights, and windows—offers both energy generation and architectural functionality. Furthermore, because of their versatility, they are perfect for off-grid or portable solar devices, such as folding panels, wearable solar chargers, and transportation-integrated photovoltaics [31][32].

Perovskite Solar Cells

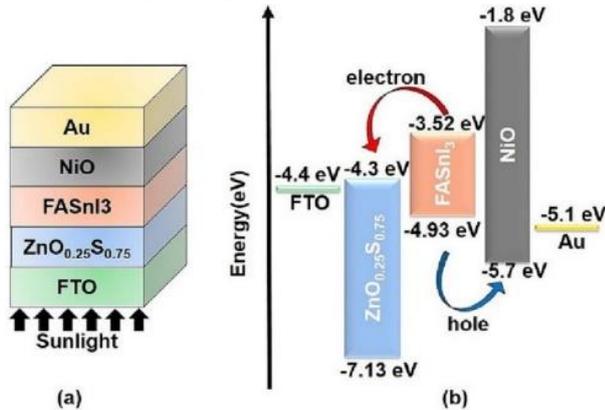


Fig.5 (a) Structure (b) Energy levels of Perovskite solar cells

Perovskite solar cells (PSCs) are among the most promising next-generation photovoltaic technologies, achieving remarkable improvements in power conversion efficiency (PCE) in a short period. From initial efficiencies of approximately 3.5%, laboratory-scale PSCs have surpassed 25% PCE in under a decade, matching the performance of established crystalline silicon cells [33] [34] [35]. This rapid advancement is due to the unique structural and electronic properties of perovskite materials, with the general formula ABX_3 , where A and B are cations and X is a halide anion. High optical absorption, low non-radiative recombination, and long charge-carrier diffusion lengths enable efficient light capture and charge transport. Combined with low-temperature, solution-based fabrication techniques, PSCs offer scalable, cost-effective production [36][37]. Perovskite silicon tandem cells exploit the solar spectrum more effectively, exceeding 29% efficiency [38][39]. Challenges remain, including moisture, oxygen, heat, and UV sensitivity, as well as lead toxicity, driving research on compositional engineering, encapsulation, and lead-free alternatives [40][41].

Challenges and Future Directions

Despite significant technological progress, solar cells still face several major challenges. One of the primary issues is stability. Advanced solar technologies such as thin-film and perovskite cells are prone to degradation when exposed to moisture, oxygen, heat, or prolonged sunlight, which gradually reduces their efficiency over time [1][40].

Toxicity is another concern, as some commonly used materials—such as lead in perovskites and cadmium in CdTe cells—pose risks to human health and the environment. This necessitates protective encapsulation, careful handling, and effective recycling strategies [1][2][40]. Scalability also remains a challenge. Many emerging solar technologies require complex manufacturing processes or highly purified materials, making large-scale production costly and difficult [6]. In addition, the overall cost of installation, protection, and maintenance increases the economic burden of solar energy systems [1][2][6]. To address these challenges, researchers are developing lead-free perovskites, tandem and multi junction devices to improve efficiency, lightweight and flexible solar panels for diverse applications, and more sustainable materials with enhanced recyclability and longer lifespans [3][12][33][44].

Conclusion

Over the past few decades, solar photovoltaic (PV) technology has advanced rapidly, transforming the way sunlight is converted into electrical energy. Crystalline silicon (c-Si) solar cells dominated early PV development and continue to be the foundation of the commercial solar industry due to their high efficiency, durability, and long operational lifetime. Mono crystalline silicon cells can achieve efficiencies of up to 25%, while polycrystalline silicon offers slightly lower efficiency at reduced cost, making it suitable for large-scale power generation. Alongside silicon-based technologies, thin-film solar cells such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon have gained attention. These technologies require less material and enable lightweight and flexible designs, which are advantageous for applications including building-integrated photovoltaic (BIPV), portable electronics, and wearable devices. However, their efficiencies are generally lower than those of conventional silicon cells. Despite these advancements, several challenges limit the widespread adoption of next-generation solar technologies. Material stability is a key issue, particularly for perovskite solar cells, which are sensitive to moisture, heat, and ultraviolet radiation. Environmental concerns also arise from the use of toxic elements such as cadmium in CdTe cells and lead in perovskites, requiring careful handling, recycling, and disposal. Additionally, achieving large-scale manufacturing while maintaining high efficiency and low cost remains a significant hurdle.

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