

Organic Electronics in Flexible Devices: Engineering Strategy, Synthesis, And Application

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Abstract. As global temperatures rise and fossil fuel reserves dwindle, the urgency to transition to renewable energy sources becomes paramount. Concentrated solar technology (CSP) together with technological advances in solar panels, especially the development of flexible solar cells, is the key to solving these global challenges. This paper reviews the evolution of solar technology, highlighting the transition from traditional rigid panels to innovative thin-film photovoltaics such as cadmium telluride (CdTe), amorphous silicon, copper indium gallium selenide (CIGS), organic polymers, and perovskite solar cells. It delves into the engineering innovations that have propelled the field forward, including printing technologies and roll-to-roll processing, and explores the burgeoning applications of flexible solar cells in wearable electronics and building-integrated photovoltaics (BIPV). The discussion extends to the potential of emerging materials and technologies to enhance efficiency, stability, and environmental sustainability. Through a comprehensive analysis, this paper underscores the pivotal role of flexible solar cells in achieving a renewable energy future, emphasizing the need for continued research and development to overcome current limitations and fully realize their transformative potential.

Keywords: Concentrated solar power (CSP), solar panel technology, flexible solar cells, thin-film photovoltaics, wearable electronics.

1. Introduction

The escalating concerns over global warming and the dwindling reserves of fossil fuels compel a critical reassessment of traditional power generation methods, pressing the need to pivot towards renewable energy sources. Concentrated Solar Power (CSP) stands out as a pivotal renewable energy technology poised to meet current and future energy requirements, showcasing its capacity for producing sustainable electricity across numerous international ventures [1].

Furthermore, solar panels play a vital role in solar technology as a core part of solar energy conversion systems. The development of traditional rigid solar panels began in the early days of space exploration to provide basic power for spacecraft. As technology has advanced, these panels have evolved, undergoing optimization and innovation to increase efficiency, reduce weight, and improve deployment. While still playing a critical role in space missions, as the demand for space exploration increases, emerging energy technologies, such as pliable solar cells, are coming to the forefront, driving innovation in solar technology to meet the energy needs of future exploration [2].

With the gradual increase in global temperatures (global warming) and depletion of fossil fuel reserves, conventional power generation is facing serious problems and there is an urgent need to shift to renewable energy technologies. Flexible solar cells represent a new trend in solar technology, utilizing thin-film technology with superior flexibility and lightweight. Compared to traditional silicon-based solar cells, they are more adaptable and can be easily integrated into a diverse array of platforms including structures and apparel. This flexibility opens up new frontiers for the widespread use of solar energy and promotes the popularization of clean energy. The lightweight nature of flexible solar cells further enables their use in lightweight structures, helping to realize a more sustainable and environmentally friendly energy future [3].

Flexible solar panels need high-efficiency materials. CdTe is a leading thin-film technology, reaching over 20% cell and 17% module efficiency. However, tellurium scarcity limits CdTe's

growth, requiring better use of tellurium and alternative materials, such as amorphous silicon, CIGS, organic polymers, perovskite, etc [4,5].

In light of recent research advancements in flexible solar panels, this paper reviews the evolution of solar technology from rigid panels to advanced thin-film photovoltaics, including amorphous silicon, CdTe, CIGS, organic polymers, and perovskite solar cells, highlighting their potential to address efficiency, stability, and environmental concerns. It emphasizes engineering innovations in fabrication and manufacturing, such as printing technologies and roll-to-roll processing and explores applications in wearable electronics and building-integrated photovoltaics (BIPV). The discussion extends to emerging materials and technologies, underscoring the role of flexible solar cells in achieving a sustainable and renewable energy future.

2. Materials for Flexible Solar Cells

2.1. Thin-Film Photovoltaics

Thin-film photovoltaics offer a promising avenue for affordable solar electricity generation. Overcoming challenges related to material availability, environmental impact, and advancing research on thinner layers are crucial for ensuring the sustainable growth of this technology. The effective collection and recycling of modules at the end of their life cycle will play a pivotal role in addressing resource-related concerns and environmental impact [6].

Perovskite solar cells are a sustainable energy technology that is manufactured using a high abundance of raw materials. The utility model has the advantages of low ecological risk, low process temperature, high energy efficiency, low cost, etc. The battery also has the advantages of being lightweight, low material cost, and mature manufacturing process, making it a huge potential for both ground-based applications and space. At the same time, perovskite solar cells have a short energy recovery time, which can quickly achieve energy returns and improve overall efficiency. Hence, this type of battery is viewed as a significant future growth trajectory for the solar energy sector [7].

CIGS solar cell is a type of thin-film photovoltaic device that utilizes a compound semiconductor material containing four elements: copper, indium, gallium, and selenium to absorb sunlight and convert it into electrical energy. CIGS solar cells boast a high-efficiency rate of up to 22.8%, rivaling that of crystalline silicon cells, with the added benefit of spectral matching through adjustable gallium/indium ratios, enhancing their compatibility with the solar spectrum. They also feature high raw material utilization due to the thinness of the CIGS absorption layer, alongside versatility in application, being deployable on both glass and flexible substrates. However, their production is marred by complexity and high costs, alongside challenges of electron non-uniformity that may impede efficiency. Additionally, the reliance on indium, a material with limited supply and fluctuating prices, poses significant challenges to the sustainability and cost-effectiveness of CIGS solar cell technology [8].

2.2. Organic and Polymer Solar Cells

An organic solar cell employs organic semiconductors in its photosensitive layer to transform light into electricity via the photovoltaic effect directly. The flexibility of these cells means they have broad application potential in areas such as portable energy, building-integrated photovoltaics, energy-saving glass, and efficient agriculture. For example, organic solar cells can be made into wearable power supplies to power smartwatches, health monitors, and other devices; they can also be made into translucent or fully transparent batteries and installed on windows or glass curtain walls to achieve the dual functions of lighting and power generation; Flexible batteries can also be made and covered on crop sheds to adjust light intensity and provide the energy needed for irrigation and fertilization.

Organic solar cells, utilizing donor and acceptor materials made from conjugated polymers or small molecules, offer structural diversity, spectral adaptability, tunable energy levels, and solution-based processing. These materials' properties critically influence sunlight absorption, exciton

generation and dissociation, as well as carrier migration and collection, ultimately affecting the cells' efficiency and stability. Organic cells stand out for their low cost, lightweight, flexibility, translucency, and capability for large-area fabrication, presenting unique advantages over traditional inorganic counterparts to cater to diverse application needs. Nonetheless, their lower efficiency, reduced stability, and shorter lifespan pose significant challenges, necessitating advancements in material design, cell architecture, and fabrication techniques to enhance photovoltaic performance and longevity [9].

2.3. Perovskite Solar Cells

Perovskite materials represent a breakthrough in solar cell technology, boasting adjustable band gaps, low exciton binding energy, high absorption coefficients, and improved defect tolerance, which collectively facilitate efficient photovoltaic conversion. These materials offer the benefits of low cost, high efficiency, and versatility in applications for flexible solar cells, suitable for diverse settings including building integration, wearable technology, and aerospace. The fabrication of perovskite films is relatively straightforward, and achievable at low temperatures through solution-based or vacuum evaporation methods, without the need for high-temperature or high-purity conditions.

The forthcoming years are anticipated to be a pivotal period for the advancement of perovskite solar cells, with efficiencies potentially reaching up to 33%, the theoretical maximum. By combining perovskite cells with silicon or other thin-film technologies, multi-junction cells can be created to further enhance efficiency. The adaptability of perovskite cells opens up numerous commercial opportunities, including the development of flexible, transparent, or tandem modules, and their integration with existing solar technologies like silicon and CIGS modules.

However, challenges such as low stability, environmental and health concerns due to high toxicity, and difficulties in large-scale fabrication hinder the widespread adoption of perovskite solar cells. Their sensitivity to environmental conditions can lead to rapid degradation, while the presence of toxic heavy metals like lead poses regulatory and health risks. Achieving uniformity and consistency in industrial-scale production remains a significant challenge, necessitating further optimization and standardization of fabrication methods [10].

For perovskite solar cells to realize their commercial potential, overcoming these hurdles is crucial. Despite the current market acceptance of certain toxic materials, as seen with cadmium telluride batteries, stricter regulations may limit the viability of technologies dependent on hazardous substances. Innovations to replace lead with safer alternatives, such as tin, or the identification of non-toxic materials with similar advantageous properties, are essential. The growing interest in perovskite photovoltaics suggests multiple pathways to commercialization, offering both competition and collaboration opportunities with established manufacturers to introduce high-performance tandem cell technologies and premium products to the market [10].

3. Advancements in Flexible Solar Cell Engineering

3.1. Fabrication and Manufacturing Techniques

Printing technology is a method of transferring ink to a substrate using a solid printing plate or an inkjet head, which enables the formation of two-dimensional patterns. There are many types of printing technologies, such as screen printing, gravure printing, inkjet printing, doctor blade printing, spray printing, etc. The advantage of printing technology is that it can use low-temperature solution processing, which reduces manufacturing costs, and it can also use flexible substrates such as plastics, which improves the flexibility of solar cells. The disadvantage of printing technology is that it requires the use of toxic solvents, which are harmful to the environment and human body, and will also affect the stability and life of solar cells. In addition, the resolution, uniformity and repeatability of printing technology also need to be improved to achieve high-efficiency solar cells.

Roll-to-roll processing is a continuous manufacturing process that can produce large quantities of products. Roll-to-roll processing means that the substrate is rolled off one roll, processed by a printing

press or other equipment, and then rolled onto another roll. The advantage of roll-to-roll processing is that it can achieve high-speed, low-cost, high-efficiency, and large-area solar cell manufacturing, and can also be combined with printing technology to achieve the construction of multi-layered solar cells. The disadvantage of roll-to-roll processing is that the tension, temperature, humidity, and other parameters of the substrate need to be controlled to ensure the quality and performance of the solar cells. It also needs to solve problems such as cleaning, drying, and cutting of the substrate.

Perovskite material is an inorganic-organic hybrid material with a special crystal structure. It has a high absorption coefficient, high carrier mobility, long carrier lifetime, adjustable band gap, etc. Advantages: It is currently one of the most promising thin film solar cell materials. Perovskite materials can realize large-area and flexible solar cells through printing technology and roll-to-roll processing and have currently reached a stable power output of 12.2%.

The organic polymer material is a macromolecular material composed of carbon, hydrogen, nitrogen, sulfur, and other elements. It touts the perks of affordability, solubility in processing, customizability, and pliability, establishing it as another key contender in the thin-film solar cell material domain. Organic polymer materials can enable large-area and flexible solar cells through printing technology and roll-to-roll processing, and module efficiencies of 16% have been achieved.

Amorphous silicon material is a material composed of randomly arranged silicon atoms. It has the advantages of low-temperature preparation, high light absorption coefficient, and low environmental impact. It is one of the earliest materials used in thin-film solar cells. Amorphous silicon materials can realize large-area and flexible solar cells through printing technology and roll-to-roll processing and have currently reached a single-layer efficiency of 10% [11].

3.2. Design Innovations in Flexible Solar Cells

The development of flexible solar cells has been characterized by significant design innovations to overcome challenges in charge transport and optical absorption encountered in traditional planar organic photovoltaics. In 2007, Carroll and colleagues pioneered fiber organic solar cells utilizing waveguide optical geometries, achieving an efficiency of 1.1%, although the reliance on costly and rigid optical fibers prompted the search for more flexible and economical substrates. Subsequently, a non-planar cylindrical device using tube and glass rod substrates is designed, with efficiencies ranging from 0.6% to 1.4%, and the introduction of flexible substrates such as polyimide-coated silica and polypropylene fibers, processed through evaporation or solution methods, emerged as cost-effective solutions. Further, carbon nanotubes (CNTs) played a significant role in material-facilitated structural innovation. Twisting CNT fiber anodes with specific layers demonstrated efficiencies of up to 1.8%. Additionally, CNT films, yarns, and single-layer graphene as counter electrodes contributed to efficiencies between 2.3% and 2.5%.

In summary, significant progress has been made towards developing flexible, lightweight, and processable organic photovoltaic textiles, showing potential for integration into wearable electronics despite challenges in light harvesting. The future of this field lies in addressing the uniformity and controllability of thin films for high-efficiency organic fiber devices, with research expected to delve into novel organic/polymer photovoltaic materials, enhanced functional interfaces, and sophisticated optical structures. The pursuit of efficient and flexible solar cells is increasingly focused on harnessing wearable solar power sources, marking a promising direction for sustainable energy technology [12].

4. Applications of Flexible Solar Cells

4.1. Wearable Electronics

The integration of solar cells into clothing and wearable devices holds significant potential, driven by advancements in textile-based solar cell technologies. These flexible and lightweight solar cells, categorized into Dye-Sensitized Solar Cells (DSSCs), Organic Solar Cells (OSCs), and Perovskite Solar Cells (PSCs), offer a promising solution for achieving clean energy in a wearable format.

Despite challenges such as fabric electrode development, stability concerns, and industrial production hurdles, the future envisions a wide array of applications. From electronic textiles to smart wearables, these solar-integrated fabrics could revolutionize industries like sports, health, military, and aerospace. The interdisciplinary nature of this research field suggests unlimited opportunities and challenges, making it a focal point for engineers and scientists aiming to address global energy needs through innovative and wearable solutions [13].

4.2. Building-Integrated Photovoltaics (BIPV)

BIPV merges flexible solar cells with construction materials, creating an aesthetically appealing and functional photovoltaic system integrated into buildings. For Building Façades, incorporating flexible solar cells into elements like glass curtain walls and roofs enhances a building's energy efficiency. In Building Shading Facilities, flexible solar cells applied to awnings and shutters offer both shade and power generation. Lastly, when used in Building Decorative Materials, such as tiles and metal roofs, flexible solar cells not only elevate the building's aesthetic appeal but also its energy efficiency [14].

5. Future Trends and Research Directions

5.1. Emerging Materials and Technologies

The quest for new substances with superior conversion rates, alongside cutting-edge engineering tactics, continues. Leading the charge in high-efficiency perovskite solar cell research, materials like $\text{CH}_3\text{NH}_3\text{PbI}_3$ and composite halides $\text{CH}_3\text{NH}_3\text{PbI}_{3-x}\text{Cl}_x$ are in the spotlight, with the potential to hit photoelectric conversion efficiencies (PCE) of 20% in mono-structures and an impressive 29% in tandem layouts. Modifying structures and tweaking band gaps could push efficiencies even higher, with single-structure perovskite cells almost touching the 30% PCE mark. The optimism around perovskite cells is fueled by the standout optoelectronic characteristics of organometallic halide perovskites, surpassing even high-performance GaAs. The high open circuit voltage (V_{oc}) integral to these halide perovskites, possibly linked to their lofty internal photoluminescence quantum efficiency, suggests room for V_{oc} enhancement through precise control of perovskite luminosity, which could contribute to elevated PCE. For commercial viability, ensuring environmental resilience and light stability stands paramount, alongside the development of encapsulation techniques and materials that resist humidity and light. Additionally, perfecting scale-up methodologies for competent module production poses significant hurdles. Moreover, the pursuit of eco-friendly perovskite solar cells demands replacing Pb with safer alternatives [15].

5.2. Environmental Impact and Sustainability

In future applications, ecological aspects of producing and deploying flexible solar cells involve an assessment of the environmental impact across various stages of their life cycle. Flexible solar cells, with abundant and low-cost raw materials, offer the advantages of versatility and clean energy generation. However, challenges include the need for optimized manufacturing, responsible material extraction, and ensuring durability for long-term use. Additionally, their short energy payback times and potential for recycling contribute to environmental benefits. Nevertheless, addressing concerns such as efficient recycling processes, minimal environmental impact, and maintaining safety standards during manufacturing and deployment is crucial. Ongoing research in thin-film technologies aims to enhance efficiency and environmental performance, but translating these advances into scalable solutions requires concerted efforts. In conclusion, achieving a delicate balance between the advantages and challenges of flexible solar cells necessitates continuous innovation, responsible practices, and a commitment to maximizing their positive environmental impact.

6. Conclusion

The evolution of flexible solar cells represents a pivotal advancement in photovoltaic technology, offering superior flexibility and lightweight properties conducive to diverse applications. From historical developments, including the shift from rigid panels to flexible cells, to the rich spectrum of materials like perovskite, the field showcases promising advancements. Technological progress in fabrication techniques, particularly roll-to-roll processing, has enabled large-scale, cost-effective production. Applications span wearable electronics, building-integrated photovoltaics, and off-grid solutions, contributing to a sustainable energy landscape. Despite challenges, such as perovskite stability and environmental impact, ongoing research and innovations position flexible solar cells as transformative agents in renewable energy, revolutionizing industries and aligning with global sustainability goals.

References

- [1] Baharoon D A, Rahman H A, Omar W Z W, et al. Historical development of concentrating solar power technologies to generate clean electricity efficiently—A review. *Renewable and Sustainable Energy Reviews*, 2015, 41: 996-1027.
- [2] Wei J, Cao D, Wang L, et al. Dynamic modeling and simulation for flexible spacecraft with flexible jointed solar panels. *International Journal of Mechanical Sciences*, 2017, 130: 558-570.
- [3] Pagliaro M, Ciriminna R, Palmisano G. Flexible solar cells. *ChemSusChem: Chemistry & Sustainability Energy & Materials*, 2008, 1(11): 880-891.
- [4] Başol B M, McCandless B. Brief review of cadmium telluride-based photovoltaic technologies. *Journal of photonics for Energy*, 2014, 4(1): 040996-040996.
- [5] McCandless B E, Sites J R. Cadmium telluride solar cells. *Handbook of photovoltaic science and engineering*, 2011: 600-641.
- [6] Fthenakis V. Sustainability of photovoltaics: The case for thin-film solar cells. *Renewable and Sustainable Energy Reviews*, 2009, 13(9): 2746-2750.
- [7] Rech B, Wagner H. Potential of amorphous silicon for solar cells. *Applied physics A*, 1999, 69: 155-167.
- [8] Ramanujam J, Singh U P. Copper indium gallium selenide based solar cells—a review. *Energy & Environmental Science*, 2017, 10(6): 1306-1319.
- [9] Günes S, Neugebauer H, Sariciftci N S. Conjugated polymer-based organic solar cells. *Chemical reviews*, 2007, 107(4): 1324-1338.
- [10] Green M A, Ho-Baillie A, Snaith H J. The emergence of perovskite solar cells. *Nature photonics*, 2014, 8(7): 506-514.
- [11] Hösel M. Large-scale roll-to-roll fabrication of organic solar cells for energy production. Department of Energy Conversion and Storage, Technical University of Denmark, 2013.
- [12] Peng M, Zou D. Flexible fiber/wire-shaped solar cells in progress: properties, materials, and designs. *Journal of Materials Chemistry A*, 2015, 3(41): 20435-20458.
- [13] Ke H, Gao M, Li S, et al. Advances and Future Prospects of Wearable Textile-and Fiber-Based Solar Cells. *Solar RRL*, 2023, 7(15): 2300109.
- [14] Peng C, Huang Y, Wu Z. Building-integrated photovoltaics (BIPV) in architectural design in China. *Energy and buildings*, 2011, 43(12): 3592-3598.
- [15] Park N G. Perovskite solar cells: an emerging photovoltaic technology. *Materials today*, 2015, 18(2): 65-72.