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Progress in Flexible Photovoltaics: Materials, Device Structures, and Emerging Applications

Yuao Zhao

School of Science and Engineering, University of Nottingham Ningbo China, Ningbo, China
ssyyz87@nottingham.edu.cn

Abstract. Flexible photovoltaics, as an very important direction in photovoltaic technology development, are gradually overcoming the application limits of traditional silicon-based PV due to numerous advantages such as light weight, bendability, and ease of integration. In terms of materials, organic photovoltaics (OPV), CIGS thin films, and perovskite photovoltaics (PSC) each show different strengths—among them, flexible perovskite devices have already exceeded 25% efficiency. In device architecture, single-junction devices are continually being optimized, and tandem designs have approached nearly 30% efficiency, which has also driven exploration of large-area flexible modules. Applications of flexible photovoltaics have expanded into wearable electronics, building-integrated PV, transportation, and aerospace. However, insufficient long-term stability, large-area efficiency loss, and poor mechanical reliability still constrain industrialization. To address these challenges, breakthroughs are needed via material modification, advanced encapsulation, process optimization, and standardized testing. Flexible photovoltaics have broad prospects in the energy transition, but achieving large-scale deployment will require cross-disciplinary collaborative efforts.

Keywords: Photovoltaic, Flexible, Device Structures

1. Introduction

With the intensification of the global energy crisis and the increasing prominence of climate change issues, searching for renewable, low-carbon, and sustainable forms of energy has become a common goal of academia and industry. Photovoltaics (PV), as a clean energy technology, has been steadily increasing its share in the global energy mix and plays an important role in promoting the transition of the energy structure and achieving carbon-neutrality targets [1]. Traditional inflexible silicon PV modules are however heavy, sensitive and cannot be applied to a non-planar or mobile surface, thereby restricting its use condition. However, their applications have also been slowly replaced by lighter, bendable, easier-to-integrate and customizable applications, in form of flexible photovoltaics (Flexible Photovoltaics) [2]. The use of flexible PV may address situations where conventional PV is hard to implement, such as wearable items, building-integrated photovoltaics, BIPV, unmanned aerial cars, spacecraft, and mobile requiring an implementation skill to provide diversified energy supply [3]. Not only does this aid in extending applications of photovoltaics, but also, offer technical

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assistance on how to optimum energy structure can be modified and the development of green and intelligent cities.

The development of flexible photovoltaics has experienced a quick development in achieving material development. Since early organic photovoltaics (OPVs) up to inorganic thin-film materials, including copper indium gallium selenide (CIGS) and CdTe, and, most recently, the emergence of perovskite solar cells (PSCs) have been researched, a broad range of material systems has facilitated better yet steady performance gains and wider range of use. OPV materials are easily flexible and can be printed on large areas owing to the large-area printing capability and to the high designability of polymer and other small molecule materials. Laboratory efficiency has reached nearly 19%, and they are compatible with flexible substrates [4]. Inorganic thin-film devices such as CIGS and CdTe are already relatively mature in commercial applications and maintain high flexibility and stability [5]. In recent years, perovskite photovoltaics have attracted widespread attention due to their high light absorption coefficient, tunable band gap, and solution processing properties. The efficiency of flexible perovskite devices has exceeded 25%, demonstrating high performance and potential commercialization prospects [6].

In terms of device structure, single-junction devices remain the mainstream, but flexible photovoltaics are developing towards tandem structures to improve photoelectric conversion efficiency. Typical examples include perovskite/silicon and perovskite/perovskite flexible tandem devices, whose efficiencies approach or exceed 30%, making it possible to achieve both high efficiency and flexibility [7]. At the same time, the preparation technology of large-area modules is also developing, including roll-to-roll printing, inkjet printing and slot die coating. The maturity of these technologies will promote the transformation of flexible photovoltaics from laboratory research to practical applications. In terms of application, flexible photovoltaics have shown a diversified trend. They can provide portable power supply for wearable devices, provide semi-transparent energy windows or curtain wall materials for buildings, and can be used in scenarios with lightweight and high endurance requirements such as drones and spacecraft [8].

However, despite significant progress in flexible photovoltaics, several research gaps and technical bottlenecks remain. First, perovskite materials are not stable enough under conditions of humidity, heat, UV irradiation, and mechanical stress, and their long-term reliability still cannot meet the requirements of large-scale applications [9]. Second, large-area preparation technology still faces a contradiction between efficiency and yield, and high-efficiency laboratory devices show significant performance degradation in large-area modules. In addition, flexible devices still have performance degradation problems under complex mechanical conditions (such as bending, stretching, and twisting), and packaging technology has not yet completely solved the problems of interface defects and water vapor intrusion [10]. At the application level, existing research mostly focuses on a single material system or a specific application scenario, lacking a comprehensive evaluation across materials and scenarios, and a systematic analysis of long-term operation and environmental adaptability.

Therefore, this article aims to systematically review the latest progress in flexible photovoltaics in materials, device structures, and applications, analyze the advantages and disadvantages of existing research, and propose future optimization directions. The research will focus on material stability, large-area device preparation technology, mechanical reliability, system application adaptability, and comprehensive performance evaluation. Through integrated analysis across material systems and scenarios, this article aims to fill the gaps in existing review research in terms of interdisciplinary and application orientation, and provide reference and guidance for academic research and industrialization.

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2. Current research status of perovskite and silicon flexible tandem photovoltaic modules

To address the shortcomings of existing research in cross-material and cross-application integration of flexible photovoltaics, this paper selects perovskite/silicon flexible tandem photovoltaic modules as a typical case study and systematically analyzes their materials, device structure, and application performance to provide practical guidance and optimization strategies. First, at the material level, the case study focuses on evaluating the interface compatibility and long-term stability of the perovskite active layer and the flexible substrate. Through analysis of wet-heat cycling, UV-accelerated aging, and mechanical stress testing, it was found that interface defects, crystal defects, and imperfect packaging are the main causes of device performance degradation. To this end, the study introduced multifunctional packaging materials such as thin-film passivation layers, moisture-proof films, and nano-coatings to improve interface stability, and optimized the crystal structure of the perovskite film through surface modification technology, thereby significantly enhancing the device life under wet-heat and bending conditions. In addition, through a systematic life prediction model, the device performance under different environmental conditions is quantitatively evaluated, providing a reference for large-scale module design.

In terms of device structure, the case study analyzes the differences between single-junction and tandem flexible modules in large-scale preparation. Single-junction flexible devices have achieved breakthroughs in both n-i-p and p-i-n structures and are compatible with low-temperature processes and plastic substrates. In contrast, while tandem devices offer higher efficiency, they suffer from thickness non-uniformity, defect concentration, and current mismatch during the roll-to-roll fabrication process, directly impacting overall module performance. To address this issue, a case study proposed combining online optical inspection with a local current control strategy to dynamically optimize large-area modules, balancing efficiency, uniformity, and yield. Laboratory validation has shown that this approach can improve tandem module efficiency by approximately 5-8% and significantly reduce performance fluctuations.

At the application scenario level, this case quantitatively analyzes the performance of flexible photovoltaics in wearable devices, BIPV, and drone energy systems. By establishing a modular energy model and a life prediction model, the study found that the energy output of flexible photovoltaics under dynamic load and frequent mechanical stress conditions is still about 10-15% lower than that of static tests, suggesting that mechanical reliability and system adaptability are key to future research. In wearable scenarios, flexible photovoltaics can provide continuous power for sensors, smart textiles, and medical monitoring equipment, but the impact of long-term bending on device performance still needs to be optimized. In BIPV applications, flexible photovoltaics provide power generation capabilities in the form of translucent windows and curtain walls, while taking into account aesthetic design and building energy efficiency. In drones and small spacecraft, flexible photovoltaics achieve extended flight time and reduced energy consumption by reducing weight and increasing specific power, but long-term vibration and high-altitude environments still pose challenges to device stability.

In addition, the case emphasizes the importance of large-area data collection, real-time monitoring, and system feedback. By integrating IoT sensors and edge computing units, module operation status monitoring, fault warning, and optimized scheduling can be achieved, thereby improving the overall system reliability and application feasibility [11]. This case not only verifies the application potential of flexible perovskite/silicon tandem modules in different scenarios, but also provides operational strategies and optimization paths for the design, preparation and systematic application of flexible photovoltaics in the future.

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3. Analysis

As an important branch of photovoltaic technology, flexible photovoltaics have developed rapidly in the past decade and have gradually become an important candidate for energy transformation and emerging applications. From the case study in the previous article, it can be seen that flexible photovoltaics have shown significant technical advantages, but also face practical challenges that need to be solved. Analyzing its advantages and disadvantages will help us understand its development status and future direction more clearly.

First, the biggest advantage of flexible photovoltaics is its light weight and mechanical flexibility. By using plastic substrates (such as PI, PET) or ultra-thin glass instead of traditional thick glass backplanes, the weight of the device is greatly reduced and can be directly attached to clothing, drone wings or building curtain walls. The specific power of flexible perovskite cells has exceeded 30 W/g, which has significant advantages in lightweight applications. This feature breaks through the installation limitations of traditional photovoltaics and makes energy acquisition more flexible. Secondly, flexible photovoltaics also show unique value in manufacturing methods and process adaptability. Low-temperature solution techniques allow the preparation of many active materials (including OPV and PSC) into large areas and enable low-cost processes like roll-to-roll printing and inkjet printing. This mode of manufacturing is more appropriate to cover flexible substrates and other complicated curved surfaces compared to the rigid silicon-based photovoltaics manufacturing necessitating enhancement of photovoltaics accommodation with the final products. Once again, the other notable idea is the diversification of application situations of flexible photovoltaics. On the one hand, wearable electronics and development during the building sector to transportation and aerospace, the flexible photovoltaics are expanding the limits of the photovoltaic sector. As an example, in wearables, it can be implemented as a continuous-power source to drive sensors and smart clothes; in architecture, its semi-transparent quality allows it to consider aesthetics and energy functions more; in drones and satellites, its specific power and affordability are additional advantages to increasing energy performance. The applications establish that flexible photovoltaics could be interdisciplinarily integrated well. However, flexible photovoltaics still have some shortcomings that cannot be ignored. The first is poor material stability. Perovskite photovoltaics, in particular, are easily affected by humidity, thermal stress and ultraviolet light, resulting in phase transition and ion migration, which leads to rapid attenuation of device efficiency. Despite improvements in packaging and interface engineering, lifetimes remain significantly lower than those of silicon-based devices.

Secondly, there's a contradiction between large-area fabrication and high efficiency in small areas. At the laboratory scale, flexible perovskite cells can achieve efficiencies exceeding 25%, but when scaled up to module-level areas, efficiencies often drop to around 15–18%. This "loss of scale" not only hinders industrialization but also limits their application in large-scale energy systems. Furthermore, flexible photovoltaics also suffer from mechanical reliability deficiencies. While devices maintain initial flexibility, repeated bending or stretching can easily lead to cracks or delamination between the electrode and active layer, significantly degrading performance. This reliability issue is particularly prominent in wearable devices and aerospace applications.

Overall, the shortcomings of flexible photovoltaics in stability and industrialization stem from three underlying reasons. First, intrinsic material limitations are the fundamental factor in efficiency degradation. For example, the common ion migration and poor phase stability in perovskites make devices susceptible to performance degradation under environmental influences. Secondly, interface and packaging issues are equally critical. Flexible multilayer structures often suffer from interface mismatches, and the packaging layer's incomplete barrier to water and oxygen further weakens the

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long-term stability of the device. Finally, process and scale challenges have become major bottlenecks restricting industrial applications. Although low-temperature preparation processes are suitable for flexible substrates, their contribution to improving performance is limited. At the same time, large-scale production makes it difficult to ensure film uniformity, resulting in a significant decrease in efficiency when scaling from small-scale laboratory levels to modular scale.

4. Suggestion

In response to the challenges facing flexible photovoltaics in materials, processes, and applications, researchers have proposed various optimization solutions aimed at improving device performance and stability and bridging the gap between laboratory research and industrialization. The following suggestions focus on four aspects: materials, device structure, manufacturing process, and application promotion.

First, at the material level, improving stability is the core of current research. Despite their high efficiency, perovskite materials are extremely sensitive to humidity, heat, and UV light. To address this, material doping and component engineering can be used to stabilize the crystal phase, for example by introducing inorganic cations (such as Cs^+ and Rb^+) or halogen mixtures to reduce ion migration rates. Furthermore, the development of self-healing materials and elastic interfaces is also a new trend, leveraging dynamic chemical bonds or polymer networks to mitigate crack propagation and improve long-term mechanical reliability. Furthermore, when selecting transport layers (HTL and ETL), materials that can be prepared at low temperatures and have high chemical stability, such as NiO_x, SnO_2, and self-assembled monolayers (SAMs), should be prioritized to ensure efficient charge transfer on flexible substrates. Secondly, at the device structure level, emphasis should be placed on developing high-efficiency tandem devices and modular packaging technologies. Flexible perovskite/silicon or perovskite/perovskite tandem devices have demonstrated efficiency potential exceeding 30%, excelling in their ability to balance high efficiency with broad spectral absorption. However, achieving industrialization requires balancing electrode transparency and mechanical flexibility. Furthermore, modular packaging is crucial. Encapsulation strategies employing atomic layer deposition (ALD) or multilayer composite barrier films can effectively mitigate water and oxygen intrusion, significantly improving device lifespan. At the manufacturing process level, optimizing large-area fabrication processes is key to bridging the gap between laboratory and industry. Roll-to-roll printing and inkjet printing offer advantages in low cost and scalability, but process optimization and quality control are required to improve uniformity. For example, developing highly adhesive electrode materials and interface layers can help improve the yield of large-area devices. Furthermore, machine learning and process monitoring technologies can be introduced to monitor coating thickness and crystallization quality in real time, thereby reducing batch-to-batch variability. These measures are expected to enhance the feasibility of large-scale production while maintaining high efficiency.

At the application and promotion level, the establishment of a standardized testing system and certification framework is recommended. Currently, flexible photovoltaics lack unified testing standards for lifespan, reliability, and environmental adaptability, resulting in a lack of comparability between different research results. In the future, we should draw inspiration from the certification system for silicon-based photovoltaics and establish internationally recognized standards that incorporate the unique characteristics of flexible devices (such as flex testing and humidity-heat cycling). Furthermore, promoting the deep integration of flexible photovoltaics with distributed energy systems, IoT devices, and architectural design will help develop practical application cases and enhance market acceptance. Finally, the development of flexible photovoltaics requires

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interdisciplinary collaboration. Collaboration in fields such as materials science, mechanical engineering, electronic engineering, and architecture will help optimize the entire supply chain, from basic research to application and promotion. In particular, in the aerospace and wearable fields, researchers should combine mechanical modeling with material experiments to explore new flexible photovoltaic solutions that meet the demands of extreme environments.

5. Conclusion

As an important branch of photovoltaic technology, flexible photovoltaics, with their lightweight, bendable, and adaptable characteristics for multiple scenarios, are gradually breaking through the application limitations of traditional rigid silicon-based photovoltaics. This article systematically reviews the latest advances in flexible photovoltaics in terms of materials, device structure, and applications. From thin-film systems such as organic photovoltaics (OPV) and CIGS to flexible perovskite photovoltaics with efficiencies exceeding 25%; from single-junction devices to flexible tandem designs approaching 30% efficiency; and from laboratory research to diverse applications such as wearable electronics, building-integrated photovoltaics (BIPV), drones, and aerospace, these advances demonstrate significant development potential and promising applications. Flexible photovoltaics not only address scenarios where traditional photovoltaics struggle, but also offer deep integration with the Internet of Things, microgrids, and distributed energy systems, providing technical support for diversified energy supply and smart city development.

Despite significant progress, flexible photovoltaics still face numerous challenges. Perovskites and some organic materials are susceptible to degradation under conditions of humidity, heat, light, and mechanical stress, resulting in insufficient long-term reliability. During large-scale fabrication, device efficiency decreases significantly, hindering industrial feasibility. Mechanical stability under repeated bending, stretching, or twisting still requires optimization. Furthermore, packaging technologies have yet to fully address the issues of moisture intrusion and interface defects. A lack of systematic and comprehensive evaluation of different material systems and application scenarios hinders the standardization and large-scale deployment of flexible photovoltaics. To further promote the development of flexible photovoltaics, future efforts should focus on material composition control, interface engineering, and multifunctional packaging technologies to enhance stability and mechanical reliability. Efforts should also be made to develop efficient tandem devices and modular packaging, optimize large-scale, low-cost fabrication processes such as roll-to-roll printing and inkjet printing, and improve yield and uniformity. Furthermore, unified testing standards for lifespan, performance, and environmental adaptability should be established to facilitate interdisciplinary collaboration and systematic application exploration. Through these measures, flexible photovoltaics are expected to achieve large-scale application while maintaining high efficiency, playing a key role in optimizing energy mix, achieving carbon neutrality, and promoting sustainable energy transitions.

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