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Wearable perovskite devices in the biomedical field

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Abstract:

Perovskites are characterized by excellent optoelectronic properties, low cost and simple manufacturing process, abundant raw materials, and high structure tunability. These are all favorable properties that enable them to be utilized in biomedical applications on a wearable basis. In this paper, the applications of two types of perovskite devices that have a promising prospect in biomedical field: Perovskite Photodetectors (PPDs) and Flexible Perovskite Solar Cells (FPSCs), are analyzed and discussed. In recent times, a number of approaches have been proposed to mitigate the fluctuation of the dark current in PPDs, their poor thermal stability and to enhance the performance of medical devices. The strategies include suppression of dark current by electric field modulation, fabrication of stable black-phase CsPbI3 films at low temperatures and fabrication of ultra-high-sensitivity graphene–perovskite composite fiber detectors. For FPSCs, this paper presents advances on stability enhancement (with dual hole transport layers), efficiency improvement (with liquid crystal elastomer interlayers), and implementation of Perovskite cells as energy source of autonomous sweat sensors under indoor light. These research results show the tremendous application potential of perovskite wearable devices in the biomedical field. Last but not least, this paper addresses future challenges and opportunities in this field, such as stability of long-term operation, scalability of the manufacturing process, and cost control.

Keywords: Perovskite devices; Biomedical; Wearables.

1. Introduction

The protection of the environment and the utilization of energy are key issues of the human community which shares a future. The demand for computing power is growing rapidly as artificial intelligence, big data and Internet of Things (IoT) technologies continue to grow and develop. The crucial issue today is where to get enough energy to satisfy this enormous demand, as a concern of the international community. Solar energy is clean energy and renewable energy, which is consistent with the concept of green development and can achieve a win-win situation between environmental protection and technological development. Commonly used PV materials may have to be extremely pure, difficult to process, and can be environmentally harmful. Perovskite materials, on the other hand, provide excellent optoelectronic properties, such as high absorption coefficients, tunable bandgaps, long carrier diffusion lengths, and high defect tolerance, making them very promising for applications. Moreover, perovskites are cheap materials to produce, and can be processed at relatively low temperatures (below 150°C) and their raw materials are abundant and widespread. Their thin-film structure can be fabricated on flexible substrate, realizing the lightweight and bendable characteristics, laying a solid foundation for their application in flexible wearable electronic devices. The demand for such devices is increasing tremendously in biomedical monitoring, point-of-care diagnostics and personal health management [1].

Wearable biomedical devices are a state-of-the-art interdisciplinary research area which combines flexible electronic technology with biosensing, energy harvesting and data processing units to allow for non-invasive continuous monitoring, early warning of disease, and precision treatment. Its essential benefits over traditional medical devices are non-invasive continuous monitoring, high spatio-temporal resolution and personalized medicine. The need for core components of a wearable biomedical device is a match with the properties of perovskite materials: lightweight; flexible; and mechanically stable. Highly sensitive perovskite photodetectors can boost the signal-to-noise ratio in converting light signals into electrical signals, and flexible perovskite solar cells can harvest energy to energize wearable systems. Both type of devices have excellent biomedical application potential [2].

Based on a theoretical analysis of perovskite structures and properties, this paper summarizes the progress of the application of wearable perovskite devices in the biomedical field in perovskite photodetectors and flexible perovskite solar cells areas. The goal is to give a theoretical understanding and tips for future research and use of wearable perovskite devices in the biomedical arena.Firstly, the article analyses the physical structure of perovskites and explains the change of structure will have an influence on the optoelectronic properties of perovskites. Then according to the differences of chemical compositions of perovskites, the article introduces the key advantages and current status of application areas of related devices of metal halide perovskites, oxide perovskites, organic-inorganic hybrid perovskites, and double perovskites. Secondly, the article focuses on the applications progresses of wearable perovskite devices in the biomedical field, analyses principles of manufacturing of perovskite photodetectors and flexible perovskite solar cells and introduces their current situations.

2. The Physical Structure of Perovskite

The general formula of perovskite crystals is ABX_3. A-site is a large cation (organic or inorganic), B-site is a small metal cation and X-site is an anion (usually a halide or oxygen). The A-site cation is bigger than the B-site cation. The whole structure is in a cubic shape, as seen in Figure 1. The cations at A sites are at the vertices of the cube. The cations at the B sites are in the center of the cube. The structure of anions at X sites is octahedral around the B sites. The exceptional design flexibility of perovskites is due to this unique “octahedral framework + cation-filled” structure. The optoelectronic properties of this material can be improved by tuning the elements of site A, site B and site X.

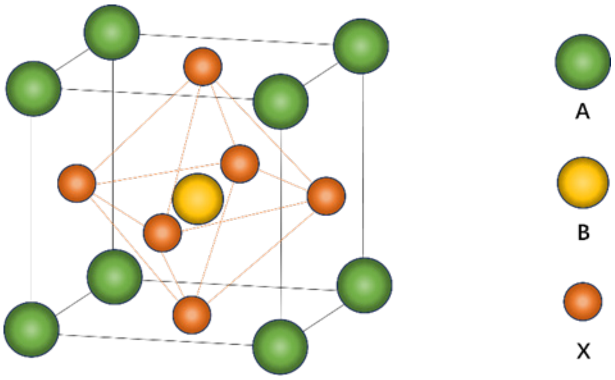

Fig. 1 Perovskite ABX_3 crystal structure.

According to the chemical composition and structure, perovskites can be divided into metal halide perovskites (MHP), oxide perovskites (OP), organic-inorganic hybrid perovskites (OIHP), and double perovskites (DP).

2.1 Metal Halide Perovskites (MHP)

Metal halide perovskites have a larger cation at the A site, which is either inorganic or organic. The B site is usually cation of divalent metal such as ions of lead and tin. The X site is occupied by a halide anion. This structural diversity helps to produce crystal structures with extraordinary optoelectronic properties including high light absorption coefficients, long carrier diffusion lengths, low exciton binding energies and high defect tolerance.

The bandgap can be tuned continuously from the visible to near-infrared spectrum by changing the halide composition or the A site cation. The transformation brings metal halide perovskites important benefits for photovoltaic devices and photodetectors. From a fabrication perspective, this material can be prepared by low temperature (LT) (<150°C) solution-based deposition.

2.2 Oxide Perovskite (OP)

In an oxide perovskite the X site is filled by an oxygen anion and the B site is normally filled by a transition metal cation, e.g., Fe2+, Mn4+, Fe3+ or Ti4+. Examples of common oxide perovskites are strontium titanate, barium titanate and lanthanum manganite. Calcium titanate perovskites are known to have excellent thermal stability (usually above 500 °C) and chemical stability as well as various functional properties including ferroelectricity, piezoelectricity and catalytic activity. They are found in applications like solid oxide fuel cells, gas sensors and memory devices.

2.3 Organic-inorganic hybrid perovskites (OIHP)

The key structure feature of the organic-inorganic hybrid perovskites is the alternating structure of organic cations and inorganic metal halide frameworks, the organic cations occupying the cubic voids formed by the inorganic framework. These materials can crystallize in three dimensional or in low dimensional structures, depending on the size and spatial arrangement of the organic groups. These are the unique properties which make the organic-inorganic hybrid perovskites to be outstanding materials: high light absorption coefficients, long carrier diffusion lengths, tunable bandgap optoelectronic properties, low temperature processability, structural flexibility and ability to be multifunctional integrated.

The intrinsic properties render it the tremendous potential for application in flexible, wearable optoelectronic devices. Moreover, the hydrophobicity, self-healing ability and biocompatibility of the material can be controlled by chemically modifying the organic cations.

2.4 Double Perovskite (DP)

The general formula of perovskite is $A_2B'B''X_6$, in which B' and B” are two kinds of metal cations with different valence. It can be considered as two kinds of B-site cations alternately in perfect order in an octahedral structure. The research directions of perovskites have been focused on mitigating the two fundamental disadvantages of lead-based metal halide perovskites: biological toxicity of lead and material stability. Lead-free materials of perovskite type can be synthesized by substituting divalent lead ions with a mixture of monovalent and trivalent metal ions. Thus, the material is well suited for application in the development of environmentally friendly, very stable optoelectronic devices.

3. Wearable Perovskite Devices: Biomedical Applications and Advances

3.1 Perovskite photodetectors

The principle of operating perovskite photodetectors is the photoelectric effect. The energy of the photons in the incident light is absorbed by the perovskite when it is larger than the width of the perovskite bandgap. When these electrons in the valence band are excited into the conduction band. This creates photo-generated electrons and holes that will move on different paths that eventually lead to the creation of a photocurrent.

To overcome the dark current instability due to defects and ion migration in polycrystalline materials, Tang et al. in 2023 proposed an electric field modulation strategy that can be applied to flexible perovskite photodetectors [3]. This technique has been able to lower the dark current by over 1000 times and was found to be effective in suppressing the ion migration. This technology can ensure long-term, stable, and uninterrupted device operation. It has been successfully applied to Wearable optical volumetric pulse wave sensor, which has significantly improved the signal to noise ratio and to further the practical application of perovskite in flexible optoelectronic detection and image sensing.

The development of flexible, wearable optoelectronic devices based on organic-inorganic hybrid perovskites (OIHP) has greatly boosted the progress in portable energy, biomedicine and sensing applications. However, they have a poor thermal stability which has restricted their use. To overcome the problem with all-inorganic perovskites, which must be annealed at high temperature, Zhao et al. solved this problem in 2025 [4]. They suggested a strategy that add diphenyl phosphonic acid chloride which can be able to form stable black-phase $CsPbI_3$ films at low temperature by an in-situ hydrolysis reaction. It greatly reduced the transition temperature and was effective to passivate defects in films. Moreover, mechanically stable flexible, wearable optoelectronic detectors were fabricated, and high precision imaging and PPG sensors were realized by exploiting the benefits of low-temperature solution processing. This technology is a novel way of making large area flexible optoelectronic devices at low temperature.

Akhavan et al. fabricated a graphene-perovskite composite fiber photodetector in 2024, which was fabricated by alternatively coating a silica fiber with a single-layer graphene (SLG) layer and a dielectric perovskite layer and exhibited a gate tunable photo response [5]. The sensitivity of this detector is ultra-high (22 KA·W-1) at a wavelength of 488 nm, which is 2 orders of magnitude greater than the current fiber optic types, and has a fast response time of 9 m/s. The photocurrent of this device is preserved at the 80% level even at bending radius of 4 mm. It can endure more than 30 wash cycles, maintaining 72% of its performance, for a long and stable photodetector unit for wearable medical monitoring.

3.2 Flexible perovskite solar cells

FPSCs are constructed of a perovskite absorption layer. It goes between a nanorod electron transport layer (ETL) and a hole transport layer (HTL). FPSCs too are deposited on flexible substrates with electrodes. Examples of the flexible substrates are polyethylene terephthalate (PET) and polyethylene naphthalate (PEN). The two main types of structures of flexible perovskite solar cells (FPSCs) are planar and mesoporous. Through the mesoporous structure, the porous titanium dioxide (m-TiO_2) film is able to well serve as a permeable medium for the penetration of perovskite material and improve the efficiency of electron extraction. Yet, it needs high temperature sintering at 450°C or above for its preparation. Planner-structured FPSCs, on the other hand, have more found uses as the charge transport materials are more compatible with low-temperature processes. FPSC devices can be categorized into the conventional n-i-p type (ETL-perovskite-HTL) and inverted p-i-n type (HTL-perovskite-ETL) based on the order of the charge transport layers. They each have different merits in terms of fabrication processes, interface control, PCE and durability.

In 2025, Rabehi et al. made a step forward towards the stability of ultra-flexible perovskite solar cells (u-FPSCs) [6]. Fabricating the nickel oxide/2PACz composite hole transport layer on a transparent polyimide substrate resulted in an inert environment photoconversion efficiency of 20.3% with stable output for 1, 200 hours. The device was integrated with a 15-nm thick moisture barrier (Al_2O_3) layer and demonstrated high environmental stability with 90% of the initial efficiency maintained after 130 hours in air, which is a new record in terms of environmental stability for u-FPSCs. It has high power density of 27.2 W g-1 and it can be integrated into flexible substrates, which paves the way for stable power supply solution to wearable medical electronics.

Huang et al. came up with the idea of placing a liquid-crystalline elastomer interlayer at the bottom interface of flexible perovskite solar cells in 2023. The researchers were able to freeze-in the molecularly ordered structure of the liquid-crystalline diacrylates and dithiol-terminated oligomers with the help of photopolymerization. This increased the charge transport pathways [7]. This strategy sees an efficiency of 22.10% for the flexible device, which retains over 80% of its starting efficiency over 1, 570 hours, and 86% of its efficiency after 5, 000 bending cycles. The flexible solar cell chip is also incorporated into a wearable haptic device with microneedle sensor array, which can be used in a VR system that provides pain perception.

In a recent study, Min et al. proposed an in-sweat wearable sweat sensor using a flexible quasi-two-dimensional perovskite solar cell (QTPSC) with more than 31% power conversion efficiency even for indoor light, and demonstrated the capability of continuous monitoring of multimodal information in 2023 [8]. It is able to continuously monitor multimodal data such as glucose level, pH, sodium ion concentration, sweat rate and skin temperature for up to 12 hours. Perovskite modules are capable of producing a stable power supply both indoors and outdoors. It overcomes the challenge of the high-power consumption and short battery life of conventional sweat sensors and provides the first stand-alone system for non-invasive metabolic monitoring.

4. Challenges and Prospects

While much research has been accomplished, there are still three challenges to address before perovskite based wearable biomedical devices can be used clinically and commercialized.

Stability of the devices in the environment is the most critical. In actual wearable use, the devices are subjected to dynamic and complex environments, including mechanical deformations, humid atmosphere, and sweat, which can further aggravate dark current drift, ion migration and degradation of the interfaces. Stability testing is mostly performed in an inert environment or at mild conditions, and there are no common stability testing specifications for wearables.

Research and development of these devices is also hampered by large scale fabrication and cost. Although spin coating is used to fabricate most high-performance devices on a small scale, large-scale printing (roll-to-roll) methods still have difficulties in achieving uniform film and repeatability. Meanwhile, some of the organic material used for transport and the organic material used for the shell come at a high price.

Besides, lead-based perovskites are biologically toxic, which is also a significant threat to environmental safety and human health. So far, research on alternative materials to lead, such as tin-based perovskites and double perovskites, has not been able to match the optoelectronic performance and stability of lead-based systems. In addition, it is not known if these materials are biocompatible or how they affect the skin when it comes into contact with them.

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Interdisciplinary research between materials science, engineering, toxicology and medicine could result in future breakthroughs by combining multiple strategies together in a synergistic manner, such as component regulation, interface passivation and high reliability packaging technologies. AI-assisted optimization can help to speed up the process of developing stable, non-toxic perovskite formulations based on existing research, while self-healing materials have the ability to autonomously repair microstructural damage. Standardization of testing procedures under conditions that mimic real world wearable situations can provide a theoretical basis for device stability. In the meantime, multifunctional integration could be an approach toward the direction of developing next generation wearable and implantable biomedical devices. It is designed to realize energy harvesting, physiological signals sensing and data processing integration. All these functions are combined on a flexible substrate for perovskite devices.

5. Conclusion

This paper elucidates the current status of development of perovskite devices by a theoretical analysis of perovskites and understanding of application of wearable perovskite devices in biomedical field. Increased efforts on the image sensing, large-area fabrication and monitoring stability of perovskite photodetectors are being made. The stability and signal to noise ratio of the devices have been further improved through an electric field modulation scheme; Low-temperature-stable black-phase $CsPbI_3$ films were realized by in-situ hydrolysis to effectively lower the phase transition temperature and passivate the defects of the films; by fabricating graphene–perovskite composite fiber detectors, ultra-high sensitivity, fast response, and excellent wash resistance were realized.

The performance of perovskite solar cells have been improved and the application prospect is also expanded. They have enhanced the environmental stability of their devices by creating a nickel oxide/2PACz composite hole transport material on a transparent polyimide substrate, strengthened charge transport pathways by introducing a liquid crystal elastomer interlayer at the bottom interface of the flexible perovskite solar cells, and created a sweat sensor for energy harvesting based on quasi-two-dimensional perovskites that enhances the endurance of the device.

The above research results indicate that the potential for application of wearable perovskite devices in the biomedical field is enormous. The theoretical results of this study can be applied to future biomedical applications and developments of wearable perovskite devices. This paper will explore the theory of Perovskites. From these bases, future research could be directed towards making breakthroughs in a couple of areas. These areas are: stability of the perovskite device and its ability to operate in a dynamic and complex environment. Cost is another factor – as perovskite devices are yet to be mass produced. One of them is toxicity control of perovskite devices.

The article merely investigates the applications progresses of wearable perovskite devices in the biomedical field about the perovskite photodetectors and flexible perovskite solar cells. The categories of wearable perovskite devices are not abundant.

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