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Application and Research Progress of Perovskite in the Field of Optoelectronic Materials

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Abstract:

Perovskite refers to a class of materials with the formula of ABO_3. These oxides were first discovered in calcium titanate compounds. Perovskite materials have attracted widespread attention in the field of contemporary photovoltaic research due to their excellent photovoltaic properties, heralding their potential as protagonists of a new generation of photovoltaic materials. Nevertheless, the stability of perovskite materials needs to be enhanced. In addition, reducing the toxicity of the materials is a key challenge in advancing their commercialization. Currently, the rapid development of perovskite in the field of optoelectronics and its unique combination of properties have laid a solid foundation for its position as a mainstream optoelectronic material of the future. Therefore, this work focuses on the properties and applications of perovskite optoelectronics. With deeper scientific research and technological innovation, perovskites have the potential to overcome existing limitations and move towards large-scale commercial production. In the future, the further application of perovskite optoelectronic materials would have far-reaching implications for the global energy transition and environmental protection.

Keywords: Perovskite; optoelectronic materials; optoelectronic application.

1. Introduction

Recently, perovskites and their related derivatives have gained widespread applications and attention in the field of optoelectronic materials science due to their flexibility in bandgap regulation, remarkable light absorption efficiency, long carrier lifetime and diffusion length [1-3]. Research efforts have been focused on solar cells, photodetectors, light-emitting diodes and nano-lasers. A wealth of theoretical and practical results have been accumulated through in-depth exploration of their working mechanism and performance. Particularly in solar cells, perovskite solar cells have become a model for third-generation high-performance thin-film cells due to their high photovoltaic conversion efficiency, cost-effectiveness, low energy consumption, and high flexibility.

In addition, perovskite light-emitting diodes (PeLEDs) are emerging as a key material for future display and lighting technologies, thanks to their high luminous efficacy, colour tunability and economical manufacturing process. Perovskites are also showing promise in photodetectors, nano-lasers and other applications. There are many types of perovskite materials. Among them, lead halide containing perovskites have attracted much attention due to their excellent performance. Subsequently, in order to accelerate the progress of perovskite materials towards commercial applications, the key challenges to be solved are to enhance the stability of the materials and to mitigate the impact of environmental toxicity of specific types of perovskites.

On this basis, the future development path of perovskite photovoltaic materials is prospectively considered and predicted in this work.

2. Photoelectric Properties of Perovskites

2.1 Photoelectric Effect

In 1905, Albert Einstein made a theoretical breakthrough that provided a novel interpretation of the phenomenon of the photoelectric effect. It is deduced that electromagnetic radiation essentially consists of particles with an energy value of hν. Meanwhile, the quantisation of electromagnetic radiation during absorption is also emphasised [1]. In general, the photoelectric effect can be divided into two main categories. The external photoelectric effect describes the phenomenon of electrons escaping when light of a specific frequency strikes the surface of a material. These escaping electrons are called photoelectrons. The internal photoelectric effect occurs when the energy carried by an incident photon exceeds the energy gap between the conduction and valence bands of a material. It causes valence band electrons to jump into the conduction band, which in turn affects the electrical conductivity of the material and the internal potential distribution. Einstein innovatively regarded the absorption process of light as a discrete quantum behaviour. This breakthrough broadened the boundaries of optical theory from the traditional fluctuation theory to the scope of quantum theory. Meanwhile, it also profoundly revealed the dual nature of light with both fluctuation and particle properties [3].

2.2 Structures and Optical Properties

The perovskite crystal structure is a complex multiphase solid state system. It is characterized by a compressed fermionic energy band material (CMR) that exhibits amorphous-crystalline properties. Traditionally, the structure involves three basic elemental components which include calcium, titanium and several coelements [4]. The calcium atoms form a face-centred cubic lattice characterised by a six-membered ring arrangement. The titanium atoms fill these six-membered rings in a broadband pattern, and the coefficients are staggered in the perovskite framework of perovskite. When external conditions such as electric fields, pressure and temperature changes are applied to the system, the local charge distribution between the perovskite atoms is adjusted, leading to changes in the macroscopic properties of the material. The central property of these crystals stems from the coupling effect, which is the force of interaction between atoms or molecules. Although the face-centred cubic arrangement of the main structure of perovskites and their spatial configuration with the coelements may only show weak steric interactions, the whole structure exhibits unique structural properties, such as optical reflection and scattering. In addition, perovskites exhibit excellent optical properties [5], including high intensity light absorption, optical emission efficiency, and tunable bandgap, which make them ideal candidates for optoelectronic devices.

3. Applications

In the field of optoelectronic materials, most of the perovskites involved are metal halide perovskites (MHPs).

3.1 Solar Cells

Calcium-titanium-mineral solar cells are gaining traction due to their superior efficiency, cost-effectiveness, lightweight flexibility, easy manufacturing process and tunability [6]. Innovative products such as tandem, flexible, building-integrated photovoltaic (BIPV) and colour-tunable photovoltaic (PV) cells have been deployed on a large scale in the desert areas of north-western China. These devices not only significantly enhancing the local power supply capacity, but also providing a strong support for the stable operation of infrastructure services.

3.2 Photodetectors

Perovskites are highly sought-after candidates for photodetectors because they exhibit excellent photosensitivity, a broad spectral response range, and excellent charge-carrying capability [7]. They can detect a wide range of wavelengths from the ultraviolet to the near infrared. It gives them the potential to be used in applications such as highly sensitive low-light detection, flexible wearable devices, high-speed communication systems, and advanced imaging technologies. Because of their diverse functionalities and excellent performance, perovskites are considered to be a very competitive direction for the next generation of photodetection technologies.

3.3 Light-Emitting Diodes

The basic composition of PeLEDs involves an electron transport layer, a hole transport layer, a light-emitting layer, the positive electrode and the negative electrode [8]. Understanding the mechanism of light emission in PeLEDs is very important. When a frontal voltage is applied, the electrons and holes recombine within the layer of perovskite. The process is accompanied by the release of energy, which is manifested as light radiation [9].

The electroluminescence of PeLEDs was first documented by Saito et al. in liquid nitrogen in 1994. At that time, it did not attract much attention due to its poor efficiency. Thereafter, the breakthrough of Friend et al. revealed the ability of PeLEDs to operate at room temperature. PeLEDs quickly attracted widespread attention from the scientific community in view of their excellent optoelectronic properties, structural simplicity and cost-effectiveness.

Recently, Wei Huang et al. has achieved remarkable results in the field of PeLEDs by accelerating the radiative compounding process through an innovative crystal growth modulation strategy, achieving a fluorescence quantum efficiency of 96%. Meanwhile, a light extraction efficiency of more than 30% was obtained. Besides, a PeLED device with an exoquantum efficiency of up to 32% was achieved. This achievement breaks the record of the efficiency of PeLEDs, and highlights the broad application prospects of PeLEDs in light-emitting display technology [10].

3.4 Nanolasers

Since the landmark invention of laser technology, miniaturisation of devices has been at the heart of research

[11]. Semiconductor lasers have traditionally been at the forefront of the investigation of miniaturised lasers, which are unrivalled in their compactness [12]. After about sixty years of technological evolution, these devices have made a significant leap from the centimetre to the millimetre scale. They have now reached the sub-micron and even the nanometre scale, which led to the birth of nano-lasers.

An innovative strategy is proposed to prepare nanolasers. The ligand-assisted triple-source co-evaporation method is adopted. In addition, an inhibitor is added to retard the crystallisation process. In this way, the passivation of the defects and dimensionality control could be obtained. This method is proved to develop perovskites thin-film laser media with excellent performance. Thereafter, the simple symmetric structure of transparent symmetric SiO_2 flakes are exploited to achieve sub-wavelength scale (120 nm) thermally evaporated perovskite laser operation at a threshold of only 13 μJ/cm^2. Besides, single-mode stability in aqueous environments for more than 20 days are also confirmed. This research provides a simple, robust and mass-producible solution for future perovskite laser designs integrated with silicon-based photonics.

4. Challenges

4.1 Stability

Perovskite materials are susceptible to degradation under conditions such as moisture, UV and high temperature [13]. Therefore, a lot of works have been done to improve the stability of perovskite. It is reported that some cations can be connected to I^- on the surface of perovskite through hydrogen bonding to passivate the ionic defects [14]. In addition, the anionic framework which exhibits dense oxygen sites could anchor the atoms of the perovskite to inhibit the degradation of the perovskite through strong Pb-O and Zn-I bonds. The regenerative nature of perovskite is also a bunker that needs to be breached by academia. The variability of its thin film properties, such as crystal size and grain boundaries, can lead to varying device performance in product quality control.

4.2 Toxicity

Currently, perovskite luminescent materials for high-performance PeLEDs are basically based on the synthesis of metal lead atoms [15]. It is well acknowledged that Pb is toxic. Meanwhile, organic and inorganic Pb-based perovskite materials are soluble in water. They can easily pollute the environment and harm human health. It can be seen that the toxicity of the heavy metal Pb hinders the further commercialisation of PeLEDs.

To address this problem, scientists have studied Sn-based, Sb-based, Bi-based, Cu-based and other lead-free PeLED materials. Among these lead-free PeLED materials, Sn-based PeLEDs is the most extensively used. However, Sb-based, Bi-based, and Cu-based PeLEDs also have good performance.

5. Conclusion

Current research has shown that, despite significant progress in the performance and application of perovskite nanolasers, their stability and toxicity remain key challenges that need to be addressed. In the future, the focus of research will shift to the development of highly stable and lead-free perovskite materials. At the same time, deepen the understanding of optic physics mechanism of perovskite materials is also important for the further applications. This would lay a solid theoretical foundation and technological support for the subsequent progress of perovskite nano-lasers.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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