International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 14 Issue 4 ǁ April 2026 ǁ PP. 127-132

Paper Title A Comprehensive Review on Metal Halide Perovskite Photodetectors: Structural Design, Mechanisms, and Stability

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Abstract

Metal halide perovskite semiconductors have garnered widespread attention in the field of photodetection owing to their exceptional optoelectronic properties, including tunable bandgaps, high absorption coefficients, long carrier lifetimes and diffusion lengths, as well as low-cost solution processability. This review systematically summarizes the recent research progress of perovskite photodetectors (PPDs) from the perspectives of material systems, device architectures, and application scenarios. We first introduce the fundamental optoelectronic properties of perovskite materials and the key performance metrics of photodetectors. Subsequently, the research progress of PPDs is elaborated from three dimensions: perovskite material systems (including three-dimensional polycrystalline films, single crystals, two-dimensional perovskites, and lead-free perovskites), device architectures (photoconductors, photodiodes, phototransistors, and self-powered devices), and emerging application scenarios (including flexible wearable devices, optical communication, X-ray imaging, and polarization-sensitive detection). Particular emphasis is placed on the analysis of strategies for balancing responsivity and response speed, the mechanisms of defect passivation and interface engineering, as well as the trade-off between sensitivity and stability. Finally, this review outlines the current challenges and future directions in the field, including stability enhancement, large-area scalable fabrication, integration with commercial platforms, and the development of application-customized device paradigms.

Keywords: *Perovskite; Photodetector; Device architecture; Self-powered; Imaging; Flexibility*

Date of Submission: 09-04-2026 Date of Acceptance: 22-04-2026

I. INTRODUCTION

Photodetectors, as core components for converting optical signals into electrical signals, play an indispensable role in modern information technology, with application scenarios spanning image sensing, optical communication, environmental monitoring, medical diagnosis, and security inspection [1,2]. While traditional inorganic photodetectors based on silicon (Si), gallium nitride (GaN), and indium gallium arsenide (InGaAs) offer mature fabrication processes and high reliability, their inherent rigidity, complex epitaxial growth requirements, and high production costs limit their application in emerging fields such as flexible wearable electronics and large-area array integration.

In recent years, metal halide perovskites have emerged as a disruptive semiconductor material system in the field of optoelectronics. Since their initial application in solar cells, perovskite materials have rapidly expanded into light-emitting diodes, lasers, and photodetectors. The exceptional optoelectronic properties of perovskites—including tunable bandgaps (covering the entire visible spectrum and extendable to the near-infrared region), high absorption coefficients (on the order of 10^4–10^5 cm^{-1}), long carrier diffusion lengths (exceeding micrometers in polycrystalline films and reaching millimeters in single crystals), and defect tolerance—render them highly desirable for high-performance photodetectors [3]. Particularly noteworthy is the solution processability of perovskites at low temperatures, which enables compatibility with flexible substrates and large-area printing techniques, opening new pathways for the development of low-cost, lightweight, and flexible photodetectors.

However, despite the remarkable progress made in the field of perovskite photodetectors (PPDs) over the past decade, several key challenges remain to be addressed before commercialization can be realized. First, the long-term operational stability of perovskite materials under ambient conditions—particularly their susceptibility to moisture, oxygen, thermal stress, and continuous light illumination—remains a primary bottleneck. Second, the inconsistency in large-area manufacturing processes makes it difficult to achieve high yield and device-to-device uniformity. Third, the toxicity of lead in conventional perovskite compositions raises environmental concerns that must be addressed for practical applications

This review provides a systematic overview of the recent research progress in perovskite photodetectors. We begin by introducing the fundamental material properties of perovskites and the key performance metrics of photodetectors. Subsequently, we elaborate on the research progress from three dimensions: material systems (3D polycrystalline films, single crystals, 2D perovskites, and lead-free perovskites), device architectures (photoconductors, photodiodes, phototransistors, and self-powered devices), and application scenarios (flexible wearables, optical communication, X-ray and imaging detection, and polarization-sensitive detection). Finally, we discuss current challenges and future perspectives, including stability enhancement, scalable fabrication, integration with commercial platforms, and the emerging paradigm of application-customized device design.

II. RESULT AND DISCUSSION

1. Perovskite Materials for Photodetectors

1.1 Three-dimensional perovskite polycrystalline films

Three-dimensional (3D) organic-inorganic hybrid perovskites, typically represented by $MAPbI_3$, $FAPbI_3$, and mixed-cation compositions such as $Cs_x(FA_{0.17}MA_{0.83})_{100-x}Pb(I_{0.83}Br_{0.17})_3$, are the most widely studied material system in perovskite photodetectors. These materials exhibit direct bandgaps, high absorption coefficients, and excellent carrier transport properties, enabling photodetectors with high responsivity and fast response times. For instance, triple-cation perovskite photodetectors based on a p-i-n architecture have demonstrated broadband responsivity of approximately 0.3 $A\cdot W^{-1}$ and rise times down to 38 μs, with specific detectivity exceeding 1×10^{12} Jones [4]. The preparation of high-quality polycrystalline films is critical to device performance. Solution processing methods including spin-coating, blade-coating, and spray-coating have been extensively explored. Among these, spin-coating yields the highest film quality but is limited to small-area fabrication, whereas blade-coating offers a scalable pathway for large-area photonic integration. The morphological robustness of triple-cation compositions suggests strong compatibility with blade-coated deposition, enabling controlled thicknesses below the grain-size threshold.

1.2 Perovskite single crystals

Compared with polycrystalline films, perovskite single crystals exhibit significantly longer carrier lifetimes, higher carrier mobilities, longer diffusion lengths, and lower trap densities, making them highly attractive for high-sensitivity photodetection. The reduced grain boundaries in single crystals minimize carrier recombination losses and suppress dark current, leading to enhanced detectivity. For ultraviolet detection, $(PEA)_2PbBr_4$ two-dimensional perovskite single crystals have demonstrated a very low dark current of 4.75×10^{-11} A, providing a low-noise baseline essential for high detectivity under weak light conditions. Even at an optical power density as low as 2.47 nW cm^{-2}, the device exhibits a responsivity of 19.23 $A\cdot W^{-1}$, with corresponding gain and specific detectivity reaching 58.80 and 1.22×10^{14} Jones, respectively [5]. The preparation of large-size, high-quality perovskite single crystals remains a challenge, with methods including inverse temperature crystallization, antisolvent vapor-assisted crystallization, and space-confined growth techniques being actively investigated.

1.3 Two-dimensional perovskites

Two-dimensional (2D) Ruddlesden-Popper (RP) perovskites, with the general formula $(RNH_3)_2A_{n-1}B_nX_{3n+1}$, have emerged as promising candidates for photodetection owing to their unique layered structure, excellent environmental stability, and mechanical flexibility. The organic spacer layers in 2D perovskites act as barriers that effectively prevent moisture and oxygen ingress, thereby significantly enhancing ambient stability compared to their 3D counterparts. However, the bandgaps of Pb-based 2D perovskite materials typically exceed 1.6 eV, limiting their absorption capability in the near-infrared (NIR) region [6]. To address this limitation, researchers have developed thermal regulation strategies to inhibit the formation of low-n phases and promote high-n phase growth in 2D perovskite films, thereby extending the absorption edge to 816 nm. Based on this optimized process, photodetectors achieved a responsivity of 0.325 $A\cdot W^{-1}$ and detectivity of 1.12×10^{11} Jones at 800 nm, with successful demonstration of high-resolution NIR imaging under weak light illumination of 0.1 μW cm^{-2} [6].

1.4 Two-dimensional perovskites

The toxicity of lead in conventional perovskite compositions poses significant environmental and health concerns, driving extensive research into lead-free alternatives based on bismuth (Bi), antimony (Sb), tin (Sn), and copper (Cu). Lead-free halide perovskite photodetectors have garnered considerable interest due to their favorable optoelectronic properties, tunable bandgaps, and light absorption characteristics. Recent advances in lead-free perovskites for photodetection have demonstrated impressive performance. For instance, tin-based quasi-single-crystal perovskite films fabricated via a simple spin-coating process exhibited high structural integrity and effective NIR response. Self-powered NIR photodetectors based on these films achieved detectivity exceeding 10^{13} Jones in the 780-890 nm range, and 64×64 pixel NIR imaging arrays enabled real-time imaging under ultra-weak NIR light (63 nW cm^{-2}), including fingerprint imaging and hidden object recognition [7]. Despite these promising results, lead-free perovskites still face challenges related to charge transport, defect density, stability, and detection range that hinder their overall photodetection performance. Various material engineering approaches, including interfacial, morphological, compositional, and heterojunction engineering, are being actively pursued to overcome these limitations.

2. Device Architectures and Working Mechanisms

2.1 Photoconductors

Photoconductor-type photodetectors feature a simple two-terminal metal-semiconductor-metal structure. Under illumination, photogenerated carriers increase the conductivity of the perovskite active layer, producing a photocurrent. The photoconductive gain in such devices can be significantly enhanced through trap states that prolong carrier lifetime, leading to high responsivity. However, this gain typically comes at the cost of slower response times due to the prolonged carrier recombination process. Recent strategies to optimize photoconductor performance include field-effect passivation approaches that effectively reduce trap state density and suppress nonradiative recombination. For example, Qiu et al [8]. implemented a dual-sided field effect passivation strategy in quasi-2D Ruddlesden–Popper perovskite photodetectors, achieving a low dark current of 9.62×10^{-11} A, an ultra-fast response time as low as 430 ns, and a linear dynamic range of 171.4 dB, which represent the highest reported detection indicators in quasi-2D perovskite photodetectors to date.

2.2 Photoconductors

Photodiode-type photodetectors, particularly those based on p-i-n or n-i-p architectures, offer the advantages of low dark current, fast response, and self-powered operation capability. In a p-i-n architecture, the perovskite intrinsic layer is sandwiched between hole transport and electron transport layers, enabling efficient carrier separation and collection even at zero bias. Comprehensive investigations of triple-cation perovskite photodetectors based on p-i-n architecture employing $Cs_x(FA_{0.17}MA_{0.83})_{100-x}Pb(I_{0.83}Br_{0.17})_{3,}$ absorbers have demonstrated outstanding performance, including suppressed dark current, reduced hysteresis, broadband responsivity, and fast temporal operation [4].

2.3 Self-powered photodetectors

Self-powered perovskite photodetectors (SPPDs), which operate without an external power supply, offer unique advantages for developing intelligent sensor networks and Internet of Things (IoT) applications. The photovoltaic effect in perovskite p-n or p-i-n junctions enables photodetection at zero bias, eliminating the need for external power sources and simplifying system integration. The working mechanisms of SPPDs can be classified based on the primary driving force for carrier separation, including built-in electric fields in heterojunctions, ferroelectric polarization, and pyro-phototronic effects. Critical strategies to enhance device performance and stability include structural and architectural optimization, advanced film fabrication techniques, and defect and interface passivation approaches [9,10].

2.4 Phototransistors

Phototransistors incorporate a gate terminal that enables active control of carrier concentration and photoconductive gain. The three-terminal architecture offers additional degrees of freedom for performance optimization, including the ability to modulate gain and response speed independently. However, the more complex fabrication process and higher operating voltages remain challenges for practical applications [11,12].

III. Emerging Applications

3.1 Flexible and wearable photodetectors

The solution processability of perovskites at low temperatures makes them inherently compatible with flexible substrates such as polyethylene terephthalate (PET) and polyimide (PI) [13,14]. Flexible photodetectors have garnered significant attention by virtue of their potential applications in environmental monitoring, wearable healthcare, imaging sensing, and portable optical communications. Significant advances have been made in developing flexible perovskite photodetectors with high mechanical stability. A nature-inspired fabrication method based on a photolithography-free flexible polymer grid has been reported for high-resolution pixelation of perovskite photodetectors, enabling ultra-flexible pixelated devices for high-resolution imaging applications. Additionally, a “soft-hard combined” structural design strategy utilizing in-situ thin-layer modification of perovskite surfaces with organosilane has been developed to produce armor-like all-inorganic perovskite active layers, achieving a good balance between stability, conductivity, and flexibility. The resulting

UV photodetector exhibited a responsivity of 13.60 mA/W and detectivity of 7.75×10^{10} Jones, maintaining 78% of initial performance after 5000 bending cycles [15].

3.2 Optical communication

Perovskite photodetectors have emerged as promising candidates for optical communication systems due to their exceptional optoelectronic properties and low-cost fabrication. They have been successfully integrated as modulated light receivers in wireless optical communication systems. A notable demonstration involved 2D Ruddlesden-Popper perovskite flexible photodetectors designed using the charge-collection narrowing principle to achieve dual-band response characteristics[16]. The detectors exhibited excellent optoelectronic performance in the visible range, with maximum responsivity reaching $0.64\ \mathrm{A\cdot W^{-1}}$ at 488 nm and $1.02\ \mathrm{A\cdot W^{-1}}$ at 532 nm, and maximum specific detectivity of 2.87×10^{12} Jones and 4.51×10^{12} Jones, respectively. The devices also showed a wide linear dynamic range of 130 dB and fast response times of 121/154 μs [17]. Based on these outstanding properties, the team developed a multiplexed encrypted communication system using 488 nm and 532 nm light as independent information transmission channels, significantly improving information transmission security [17]. A wireless optical communication system was also demonstrated for real-time vehicle localization and bidirectional information transmission.

3.3 X-ray and imaging detection

Metal halide perovskites have become highly promising candidates for next-generation X-ray detectors due to their high atomic numbers, large carrier mobility-lifetime products ($\mu\tau$), and low-cost solution processability. X-ray detectors based on perovskites are finding important applications in medical diagnosis, industrial inspection, and security screening. Recent breakthroughs in perovskite X-ray detection include the development of lead-free perovskite single crystals such as $Cs_4MnBi_2Cl_{12}$, which achieved a sensitivity as high as 2.1×10^3 μC $\mathrm{Gyair^{-1}\ cm^{-2}}$ and a low detection limit of 1.05 $\mathrm{nGyair\ s^{-1}}$, with excellent operational stability even at temperatures up to 100 °C [18]. Quasi-one-dimensional perovskite single crystals have also been developed to decouple ionic and electronic transport, simultaneously achieving efficient carrier collection and suppressed ion migration, with a sensitivity of 1.42×10^5 μC $\mathrm{Gy^{-1}\ cm^{-2}}$ and low current drift [19]. For imaging applications, large-area integration strategies have been demonstrated, including screen-printed perovskite CMOS focal plane arrays achieving high-performance dynamic X-ray imaging with mobility-lifetime products up to $5.2\times10^{-4}\ \mathrm{cm^2\ V^{-1}}$ [20]. Furthermore, multi-energy X-ray detection and imaging have been realized by designing unipolar n-i-n detectors that enable selective carrier collection through working voltage regulation, achieving 4-channel X-ray imaging within 20 seconds using a conventional X-ray source [21].

IV. Stability, Scalability, and Future Directions

Despite the remarkable progress in perovskite photodetectors, several critical challenges must be addressed to enable practical applications and commercialization. The long-term operational stability of perovskite materials remains the primary bottleneck. Under ambient conditions, perovskites are susceptible to degradation from moisture, oxygen, thermal stress, and continuous light illumination [22]. Strategies to enhance stability include compositional engineering (e.g., mixed-cation formulations), dimensional reduction (e.g., 2D perovskites), encapsulation technologies, and the development of all-inorganic perovskite compositions [23]. Scalable manufacturing presents another major challenge. While spin-coating yields high-quality films, it is unsuitable for large-area production. Transition to scalable techniques such as blade-coating, slot-die coating, and inkjet printing requires precise control over crystallization kinetics to achieve uniform film formation across large areas. The morphological robustness of certain compositions, such as triple-cation perovskites, suggests strong compatibility with blade-coated deposition, offering a promising route toward scalable fabrication. Integration with established commercial platforms represents a critical pathway toward practical applications. Recent work has successfully demonstrated the monolithic integration of perovskite NIR photodetectors with commercial TFT readout circuits to realize perovskite NIR imaging chips, achieving clear imaging of typical patterns at 980 nm illumination with a spatial resolution of 1.32 line pairs per millimeter [7]. Such integration strategies are essential for translating laboratory-scale device performance into practical imaging systems. Looking forward, the paradigm of application-customized photodetectors is gaining increasing attention. Perovskite materials, with their unique combination of high customizability and low customization cost, are well-positioned to establish an irreplaceable position in customized optoelectronics. Future development should target emerging application scenarios including shape-customized photodetectors, feature-selective photodetectors, multi-dimensional photodetectors, and neuromorphic vision sensors. These new paradigms are expected to form differentiated advantages in areas driven by wearable electronics, complex scene recognition, heterogeneous integration, and intelligent vision. Key challenges to be overcome include material and device stability enhancement, establishment of reliability and lifetime evaluation standards, and development of scalable integration manufacturing processes [24].

V. CONCLUSION

Metal halide perovskite photodetectors have made remarkable progress over the past decade, with performance metrics in responsivity, detectivity, and response speed continuously advancing. The exceptional optoelectronic properties of perovskites—including tunable bandgaps, high absorption coefficients, long carrier diffusion lengths, and defect tolerance—coupled with their low-temperature solution processability, have positioned them as promising candidates for next-generation photodetection technologies. This review has systematically summarized the research progress in perovskite photodetectors from the perspectives of material systems, device architectures, and application scenarios. In terms of material systems, we have discussed 3D polycrystalline films offering balanced performance and processability, single crystals providing ultra-high sensitivity, 2D perovskites delivering enhanced stability and mechanical flexibility, and lead-free alternatives addressing environmental concerns. Regarding device architectures, we have compared photoconductors offering high gain at the cost of response speed, photodiodes enabling fast self-powered operation, and phototransistors providing active control capabilities. In application domains, we have highlighted flexible wearable devices, optical communication systems, X-ray and imaging detection, and polarization-sensitive detection as key areas where perovskite photodetectors are demonstrating unique advantages. The transition from fundamental research to practical applications faces several critical challenges that require concerted efforts from the research community. Stability enhancement through compositional engineering, dimensional reduction, encapsulation, and all-inorganic formulations remains the top priority. Scalable manufacturing processes that enable large-area uniform film formation while maintaining high device performance must be developed. Integration with established commercial platforms such as TFT readout circuits and CMOS chips is essential for practical imaging systems. Finally, the paradigm shift from performance benchmarking against mature technologies to application-customized device design offers a unique opportunity for perovskite photodetectors to establish differentiated advantages in emerging application domains.

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