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REVIEWS

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Recent progress on stability and applications of flexible perovskite photodetectors

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Abstract: Flexible photodetectors have garnered significant attention by virtue of their potential applications in environmental monitoring, wearable healthcare, imaging sensing, and portable optical communications. Perovskites stand out as particularly promising materials for photodetectors, offering exceptional optoelectronic properties, tunable band gaps, low-temperature solution processing, and notable mechanical flexibility. In this review, we explore the latest progress in flexible perovskite photodetectors, emphasizing the strategies developed for photoactive materials and device structures to enhance optoelectronic performance and stability. Additionally, we discuss typical applications of these devices and offer insights into future directions and potential applications.

Key words: perovskite; flexible photodetector; stability; versatile applications

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1. Introduction

Photodetectors play a vital role in modern information society through the conversion of optical signals to electrical signals[1]. Plenty of studies in the fields of medical diagnostics, imaging, communications, and environmental monitoring have progressed the development of photodetectors for a variety of industrial, military, and civilian applications[2, 3]. The basic structures of photodetectors including photoconductors, photodiodes, and phototransistors give them different characteristics, for instance, weak light response, fast response, self-driving response, etc.[4–6]. Numerous research progress focuses on exploring advanced photosensitive materials, optimizing device structure, and proposing fabrication processes to enhance optoelectronic performance and functional diversification[7–9]. Compared with traditional rigid devices, flexible photodetectors have drawn more attention due to their superior mechanical properties which indicate considerable promise for wearable and portable optoelectronic devices. The bending characteristics of flexible photodetectors not only make them compatible with complex environments such as human skin and curved surfaces but also enable the development of special applications, for example, spatial light detection and bionic vision imaging[10–12]. Moreover, when miniaturized, arrayed, and integrated, flexible photodetectors can form contactless photoelectric interfaces. These are essential for the creation of intelligent systems and cutting-edge human-machine interactions[13, 14]. Although numerous researchers have focused on enhancing the flexibility and compatibility of photosensitive materials with flexible substrates, achieving a combination of high performance and mechanical stability remains the primary challenge for the widespread adoption of flexible photodetectors[15]. To address this issue, researchers have paid a lot of attention to the utilization of perovskite materials with an ABX_3 structure (A represents organic or inorganic cations, B represents metal ions, and X represents halogen ions) for efficient and robust flexible photodetectors.

Perovskite materials are regarded as a promising candidate for flexible photodetectors because of their remarkable optoelectronic properties, low-temperature solution preparation process, and mechanical flexibility[16]. Flexible photodetectors, utilizing perovskites across various dimensions from 0D quantum dots to 3D nanocrystalline films, have been explored for their potential in creating high-performance, stable, and multifunctional optoelectronic device[17, 18]. However, the unfavorable stability of flexible perovskite photodetectors (FPPDs) has become a great challenge for practical applicability. On one hand, the instability of perovskite materials is due to their intrinsic structural vulnerability, which leads to phase transition and phase separation under external conditions such as humidity, illumination, and electric fields[19, 20]. On the other hand, the mismatch in thermal expansion coefficients between the perovskite materials and flexible substrates, along with additional cracks caused by bending, leads to poorer operational stability compared to rigid

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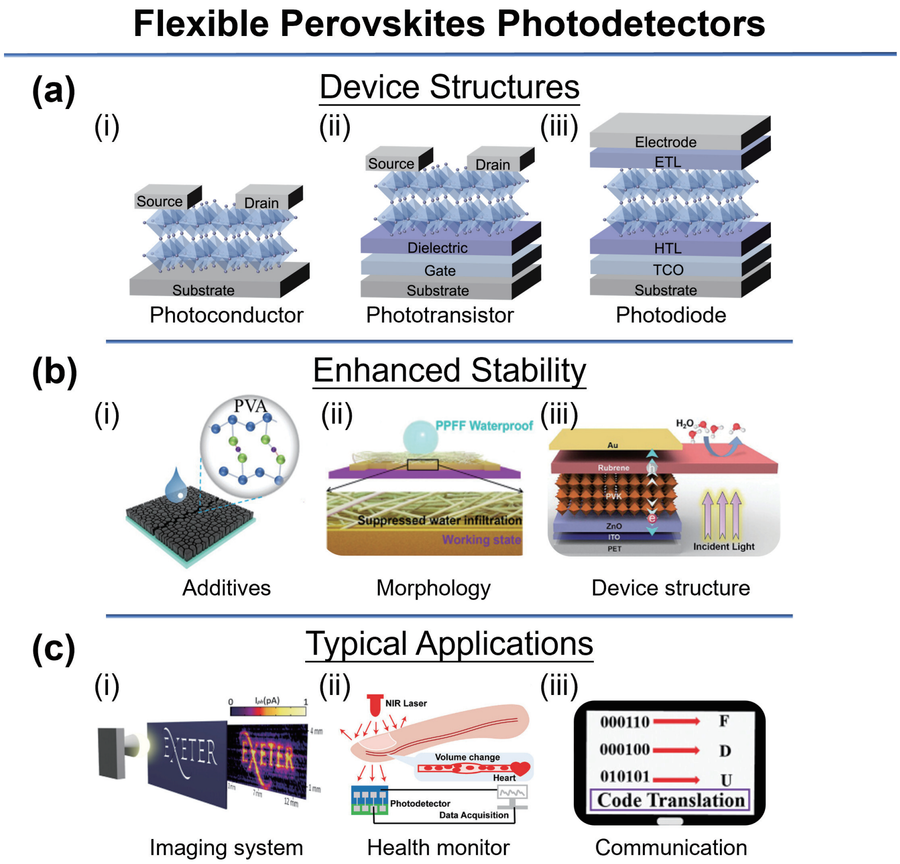

Fig. 1. (Color online) Overview of the current research on FPPDs. (a) Diagram of three kinds of device structures of FPPDs: (i) photoconductor, (ii) phototransistor, and (iii) photodiode. (b) Schematic diagram of the typical strategies for enhancing stability: (i) Mechanism of the self-healing process induced by additive. Reproduced with permission from Ref. [62]. Copyright 2021 Wiley-VCH. (ii) Stability and self-healing of composite fibrous-based photodetectors. Reproduced with permission from Ref. [67]. Copyright 2023 American Chemical Society. (iii) Rubrene protective layer. Reproduced with permission from Ref. [78]. Copyright 2023 Wiley-VCH. (c) Schematic diagram of typical applications: (i) Schematic diagram of the imaging process. Reproduced with permission from Ref. [82]. (ii) Schematic diagram of photoplethysmography test. Reproduced with permission from Ref. [92]. Copyright 2024 Wiley-VCH. (iii) Binary code conversion. Reproduced with permission from Ref. [98]. Copyright 2023 Wiley-VCH.

devices[16, 21].

To tackle the instability issue, researchers have devised several strategies such as optimizing material composition, designing device structures, and employing interface passivation. These approaches aim to enhance the intrinsic stability of the materials and improve contact at the interfaces[22−24]. In addition, the appropriate functional and protective layers can also regulate the remnants strain and repair mechanical cracks in the perovskite films, thereby improving long-term stability[25, 26]. Nevertheless, the flexibility of perovskites is achieved by altering their morphology or reducing the dimensions of the nanomaterials, given their inherent brittleness. This indicates that the aforementioned strategies may not be sufficiently universal. Consequently, further systematic research is crucial to develop methods that enhance the stability of FPPDs.

Researches on FPPDs are conducted across three key areas: device structure design, stability enhancement, and the development of multifunctional applications (Fig. 1). In this work, we present an overview of recent progress in enhancing the stability and optoelectronic properties of FPPDs. Initially, we introduce perovskite photodetectors, covering their basic structures, operating principles, and key parameters. We then outline strategies to enhance the mechanical and environmental stability of FPPDs, focusing on three areas: additive engineering, crystal morphology, and device structure. Following this, we examine the current applications of FPPDs in imaging, monitoring, and optical communication. Finally, we discuss the challenges and future prospects for the advancement of FPPDs.

2. Structures and parameters

2.1. Structures and principles of FPPDs

Perovskite photodetectors function through the internal photoelectric effect, where photons striking the photoactive materials alter their electrochemical properties. This includes changes in resistivity and the creation of photon-induced voltage, known respectively as the photoconductive effect and the photovoltaic effect, as displayed in Fig. 2. The photoconductive effect occurs when a semiconductor absorbs incident photons, generating electron–hole pairs and thereby increasing its conductivity, as illustrated in Fig. 2(a). And Fig. 2(b) demonstrates the photovoltaic effect, where exposure to light on a non-uniform semiconductor or at the interface between a semiconductor and metal induces photovoltage owing to the influence of the built-in electric field. Based on their structures and operating principles, photodetectors are classified into three categories: photoconductors, photo-

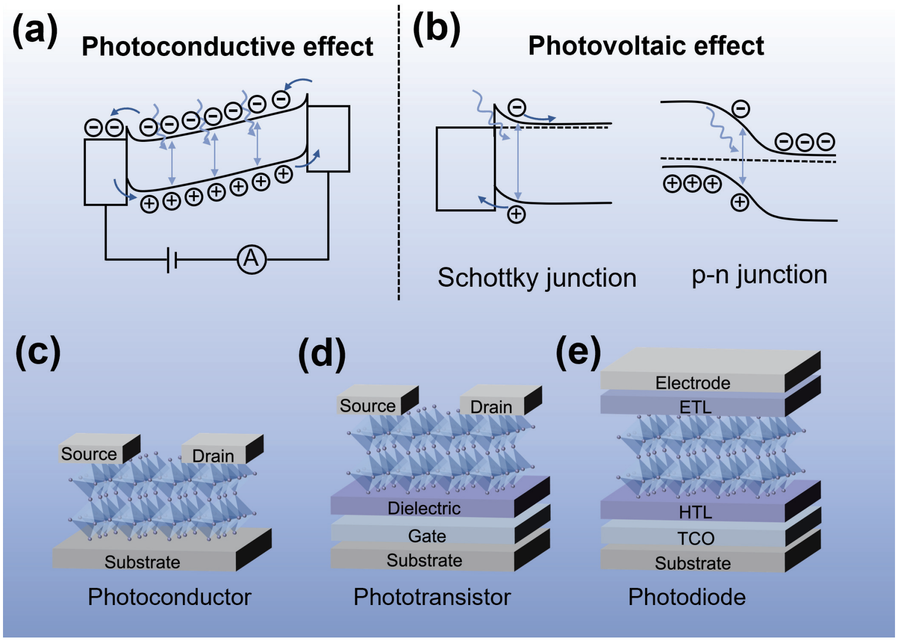

Fig. 2. (Color online) Principles and structure of different photodetectors. Schematic diagram of (a) the photoconductive effect and (b) the photovoltaic effect. Diagram of three kinds of device structures of photodetectors: (c) photoconductor, (d) phototransistor, and (e) photodiode.

transistors, and photodiodes.

A photoconductor is composed of metal–semiconductor–metal where the electrons and holes in the semiconductor are separated and transmitted towards the anode and cathode respectively to form a dark current under external voltage (Fig. 2(c)). Under illumination, photogenerated carriers are generated by interband transitions or transitions involving energy levels in band gaps, increasing conductivity and photocurrent. Moreover, photoconductor is widely used in photodetection due to its simple transverse structure and high photoconductance gain, but the long carrier transmission distance leads to a high operating voltage and a slow response speed[27]. Numerous studies have focused on enhancing the performance of photoconductive photodetectors using perovskite single crystals and nanocrystalline films[28, 29]. The potential applications of flexible integrated optoelectronic systems, characterized by high sensitivity and adaptability, have been demonstrated through the fabrication of ultra-thin crystalline films and patterned nanofilms using nanoimprint technology[30–32]. Additionally, the traditional preparing process leads to defective states at the interface between metal and semiconductor, leading to the narrowing of the Schottky barrier and the increase of dark current. Novel 2D materials are introduced as electrodes to reduce the reverse tunneling current, enabling weak-light detection and flexible applications[33].

On the other hand, a phototransistor is a photosensitive field-effect transistor consist of a photoactive layer, a dielectric layer, and electrodes (source, gate, and drain) as shown in Fig. 2(d) where photogenerated carriers generate current through the conductive channel driven by the voltage between source and drain which further amplifies the signal under gate voltage control. Compared to the photoconductor, the phototransistor has higher optical gain, slower response speed, and a more complex fabrication process. To achieve high-performance and fast response, many researchers focus on structure design and defect passivation[34], among which vertical phototransistors based on perovskite/high-mobility semiconductor heterojunction show significant application prospects in high-performance and low-cost optoelectronic devices[35, 36], especially in flexible optoelectronic devices[37].

The structure of photodiode-typed photodetector includes p–n heterjunction and p–i–n junction, in which the space charge region separates photogenerated electrons and holes to achieve an optical response. Heterojunctions are widely used in perovskite photodetectors, which can not only promote the separation and transport of photoexcited carriers to improve the device response[38, 39], but also regulate crystal growth and enhance stability[40, 41]. Energy level matching, structural design, and fabrication process of high-quality heterojunction are the main research directions to increase the photodetection performance and mechanical flexibility of flexible devices[42, 43]. In addition, the piezo-photoelectric effect may become an advanced method for high-performance FPPDs, which combines perovskites with piezoelectric semiconductors or uses the piezoelectric polarization characteristics of perovskites to regulate carrier separation, transport, and recombination by adjusting the band alignment of the interface during bending[44, 45].

Fig. 2(e) illustrates the structure of vertical photodetectors with a sandwich structure similar to perovskite solar cells in which photoactive layer is embedded between the electron transport layer (ETL) and the hole transport layer (HTL) for better extraction and transport of photogenerated electrons and holes. Since the vertical structure is known to have better mechanical flexibility[46], plentiful investigations have been carried out using component, interface, additive engineerings, etc., to create high-performance and reliable FPPDs[31, 47].

2.2. Key parameters of photodetectors

To precisely describe the performance of photodetectors, the following characteristic parameters and key requirements are briefly presented.

On/off ratio*:* The on/off ratio is calculated from the ratio of photocurrent to dark current which indicates the sensitivity to light signal. The dark current is an inevitable and undesirable current that occurs as a result of thermal effects, carrier injection, recombination, tunneling, etc.[48]. The photocurrent refers to the increased current under illumination and is related to the ability to absorb and convert light.

Responsivity: Responsivity (*R*) is a common parameter reflecting the response sensitivity of photodetectors, which is measured by the ratio of photocurrent to incident light intensity:

$$R = \frac{I_{\mathrm{ph}} - I_{\mathrm{dark}}}{P_{\lambda} S}, \tag{1}$$

where I_{ph} and I_{dark} represent the photocurrent and dark current of photodetectors, P_{λ} corresponds to the power density of incident light at a particular wavelength, and S refers to the effective illumination area, respectively.

Noise equivalent power: Noise equivalent power (NEP) denotes the minimum incident optical power that can be distinguished from noise. In other words, NEP is the value of light power when the photocurrent generated by the incident light is exactly equal to the noise current. It is defined as:

$$\mathrm{NEP} = \frac{I_n}{R}, \tag{2}$$

where the I_{n} and R refer to the noise current and responsivity, respectively.

Detectivity: Detectivity is the reciprocal of the NEP and indicates the detective sensitivity to weak signals. The specific detectivity (D*) obtained by normalizing the effective area and bandwidth, which is used to visually compare the detection capabilities of different devices, and is calculated as follows:

$$D^* = \frac{R\sqrt{S}}{\sqrt{2eI_{dark}}}, \tag{3}$$

where R, S, e, I_{dark} represent the responsibility, effective illumination area, electronic charge, and dark current, respectively.

External quantum efficiency: External quantum efficiency (EQE) is defined as the ratio of the number of electrons collected to the number of incident photons, and is crucial for assessing the efficiency of photodetectors with which incident photons are transformed into current. It is calculated as:

$$\mathrm{EQE} = \frac{hc}{e} \cdot \frac{R}{\lambda}, \tag{4}$$

where h, c, R, e, λ represent the Planck constant, light viscosity, responsibility, electronic charge, and incident optical wavelength, respectively.

Response time: The response speed of photodetectors is described by response time during the on and off of the incident light. The response time is made up of the rise time (τ_{rise}) and the delay time (τ_{decay}), which are defined as the period when the photocurrent goes from 10% to 90% and from 90% to 10% of the maximum photocurrent, respectively.

Stability: Stability is a crucial requirement for flexible perovskite optoelectronic devices, which are usually evaluated by optoelectronic performance testing after cyclic bending, or switching the device under specific conditions (e.g., bending radius, temperature, humidity, etc.).

The fundamental structures, working principles, and key performance parameters of photodetectors are introduced, serving as an orientation for assessing the performance of FPPDs. Furthermore, it is also crucial to account for the detection spectrum window, spectral response, and dynamic range of photodetectors.

3. Strategies for stability improvement of FPPDs

To achieve high-performance, reliable applications, the basic requirements for FPPDs include structural and mechanical stability. The structural instability including the transformation, separation, and degradation of the perovskite phase, has been widely discussed and addressed in rigid devices[49, 50]. Optimizing the perovskite layer to inhibit defect states and ion migration is also crucial in FPPDs[51]. In terms of mechanical stability, the compatibility of materials with flexible substrates (polymer, paper, fiber, etc.) and the properties retained after deformation (bending, stretching, torsion, etc.) are primary considerations. This physical distortion has both negative and positive impacts on flexible devices. On the one hand, the cracks generated during the deformation process impede the transport of carriers and accelerate the degradation of perovskites result in the attenuation of FPPDs. On the other hand, moderate bending can release the strain caused by interface mismatch and improve the stability of perovskite films[52]. Here, three paths of additive engineering, crystal morphology optimization, and device structural optimization are introduced to raise the stability of FPPDs.

3.1. Additive engineering

The flexibility of perovskite materials is derived from the low modulus of elasticity, which is determined by the cation at the A position and the B-X framework, making it feasible to advance mechanical stability through material composition and morphological control[53−55].

The introduction of additives including metal ions and organic small molecules to regulate the crystallization process is a practical method for optimizing the morphology and quality of perovskite films. He *et al.* introduced phenylethylammonium iodide (PEAI) additive to regulate nucleation and grain growth and successfully constructed an air-stable $FASnI_3$ flexible photodetector[56]. As shown in Fig. 3(a), the peak strength of the (100) crystal plane increased with the addition of 20% PEA^+ to the $FASnI_3$ perovskite film, indicating that PEA^+ substitution effectively modulated the oriented crystal growth of the $FASnI_3$ film, and resulted in a highly crystalline, pinhole-free, air-stable perovskite film. In addition, the introduction of PEA^+ could slowly release the crystal strain of the obtained perovskite film and form a strong C=N bond with FA^+, which significantly improved mechanical stability. Fig. 3(b) exhibits the current and responsivity curves of the unpackaged device for cyclic switching in air and under different bending conditions. The photocurrent was gradually reduced from 9.3 to 1.1 nA after 13 500 continuous test cycles over 7.5 h in air and the responsivity retained

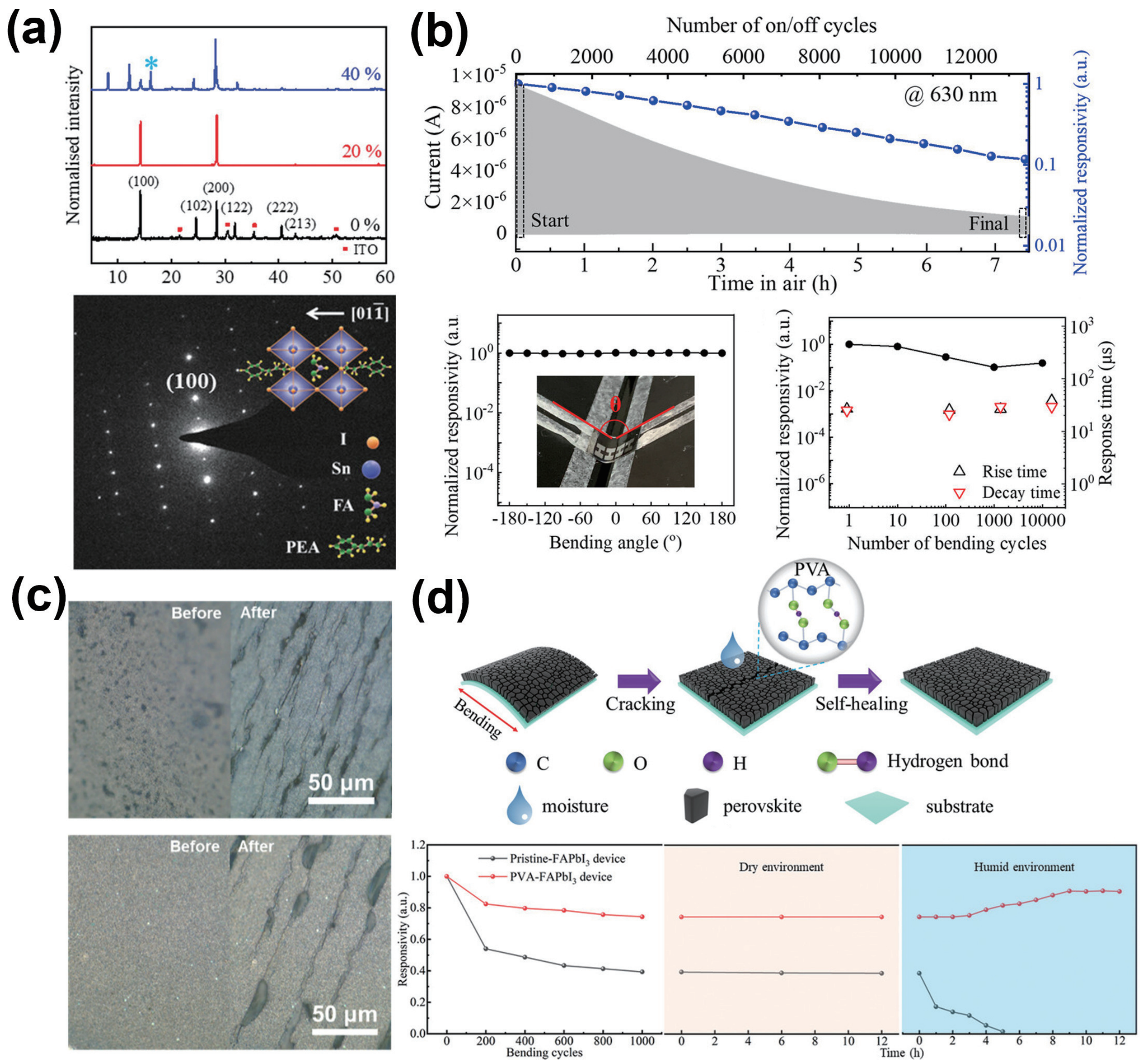

Fig. 3. (Color online) Additive engineering in FPPDs (a) XRD and TEM results of $FASnI_3$ films. (b) Operative and bending stability of the device. (a) and (b) are reproduced with permission from Ref. [56]. Copyright 2023 Wiley-VCH. (c) Optical images of crack evolution in $CsBi_3I_{10}$ films. Reproduced with permission from Ref. [57]. Copyright 2024 American Chemical Society. (d) Mechanism of the self-healing process and responsivity change. Reproduced with permission from Ref. [62]. Copyright 2021 Wiley-VCH.

constant with varying bending angles, decreasing insignificantly after 10 000 bending cycles, suggesting relatively stable operative and bending stability. The response time was maintained at 30 s after 10 000 bending cycles revealing outstanding response speed. Compared with rigid materials, flexible substrates tend to be coarser, resulting in a larger roughness for the prepared perovskite films. Wei *et al.* doped $CsBi_3I_{10}$ with polyvinylcarbazole to obtain films with smoother surfaces and reduced cracks after bending as shown in Fig. 3(c), which improved flexibility and charge transport at the interface between the films and the electrode by filling the gaps in the $CsBi_3I_{10}$ films and reducing roughness[57]. It was found that the undoped device had an open circuit after 40 cycles and a photocurrent loss of 70% after 50 bending cycles. In the case of undoped device, the photocurrent retained 72% of its original value after 100 folding cycles. Dao *et al.* incorporated Zn dopants and cellulose nanocrystals (CNC) into the perovskite precursor to synthesize highly stable perovskite papers and then constructed substrate-free FPPDs with excellent bending resistance[58]. The as-fabricated paper photodetector still maintained 65% of its initial responsivity after 30 days of storage in external environment, while the CNC-free perovskite films degraded on the substrate after three days.

The self-healing properties of materials refer to the restoration of structure and function through dynamic repair mechanisms, reducing the vulnerability to moisture, constant sunlight, and mechanical damage[59]. Previous research has demonstrated that the degradation of photoelectric properties caused by light soaking results from the photo-activated deep-level trap states, which can completely self-heal by storing in the dark for less than 1 min[60]. Wang *et al.* revealed a similar self-healing phenomenon after thoroughly investigating the impact of humidity on the photoelectric properties and flexible of two-dimensional FPPDs[61]. The formation of perovskite hydrate under high humidity irradiation led to the decrease of the dark current, which gradually recovered in darkness due to the reformation of perovskites. Although the cracks generated by bending could impair carrier transport and reduce responsivity, the responsivity increased at differ-

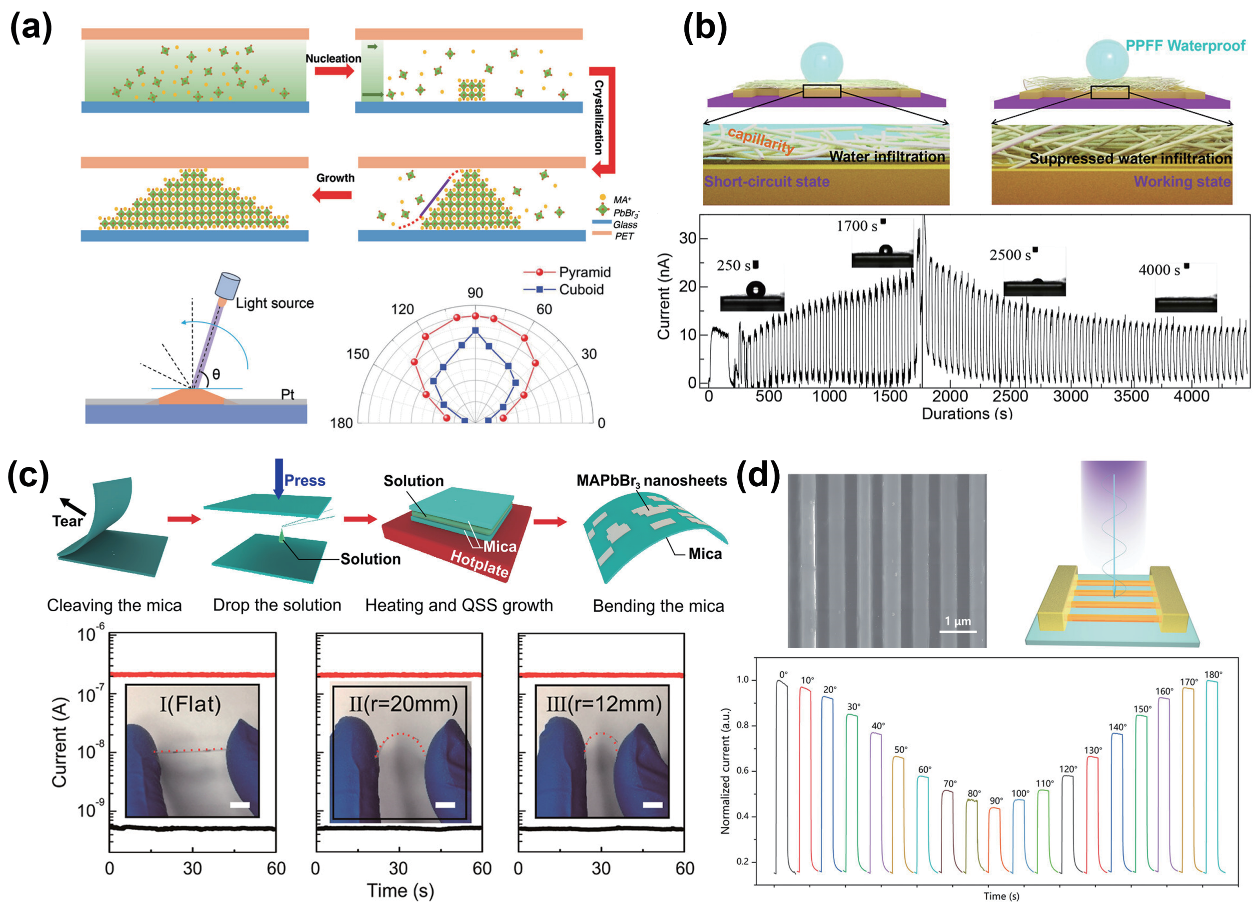

Fig. 4. (Color online) FPPDs based on different crystal morphologies. (a) Schematic diagram of crystals growing process and the photodetector performance depending on different incident light angles. Reproduced with permission from Ref. [66]. Copyright 2024 Wiley-VCH. (b) Stability and self-healing of dry-transferred capacitive contact photodetectors. Reproduced with permission from Ref. [67]. Copyright 2023 American Chemical Society. (c) Schematic representations of the solution growth and *I*–*t* curves of the device in different bending angles. Reproduced with permission from Ref. [68]. Copyright (2020) American Chemical Society. (d) The highly ordered array of $CsCu_2I_3$ and the polarization sensitivity performance of $CsCu_2I_3$ nanowires photodetector. Reproduced with permission from Ref. [70]. Copyright 2023 Wiley-VCH.

ent bending angles as the humidity increased from 35% to 70%, which means that moderate humidity may be advantageous for strengthening the flexibility of the paper-based optoelectronics. Organic polymers are utilized as additives to impart self-supporting and self-healing properties to perovskite films. Fig. 3(d) illustrates the introduction of poly(vinyl alcohol) (PVA) into perovskite to repair physical damage by capturing water molecules from the ambient atmosphere, and improve operational stability in high-humidity environments[62]. After 1000 bending cycles, the responsivity of the photodetectors with PVA and without PVA dropped to 75% and 40%, respectively. In a high humidity environment, the device with PVA additive retained 90% of its original performance, while the control film degraded rapidly.

Ion migration is one of the fatal factors causing hysteresis behavior and device degradation in photoelectric response, especially the migration of halogen anions of mixed halogen perovskites under light, accompanied by phase separation. Large A-site cations can be inserted to decrease the dimension of the perovskite and inhibit ion migration to reduce dark current and promote the stability of perovskite photodetectors[63]. Although a variety of additives, including organic salts and ionic liquids, have been shown to inhibit ion migration and heighten the operational stabilization of devices, these studies have mainly focused on light-emitting diodes and solar cells, and the impact on photoelectric detection performance is lacking[64].

3.2. Crystal morphology optimization

In addition to the common flat and uniform nanocrystalline films, perovskite devices based on different nanocrystal structures can achieve excellent flexibility, and diverse shapes endow the devices with special properties and functions[65]. As depicted in Fig. 4(a), Li grew the pyramidal structure of single crystal perovskite using the asymmetric spatially confined induced crystallization method[66]. The photodetector built on a flexible substrate demonstrated excellent bending flexibility and could sustain high-performance detection at any angle of incident light. Compared to the conventional cuboid crystals, the pyramidal crystals exhibited different angle insensitivity. Jing *et al.* synthesized perovskite/PMMA composite fiber membranes by electrospinning, and combined with dry transfer technology to construct FPPDs, which showed excellent waterproof stability and flexibility as seen in Fig. 4(b)[67]. After water droplets were placed on the surface of the photodetector, the photocurrent first increased to twice of the original value, then decreased, and finally showed 100% performance recovery, while the dark current was almost unchanged during this process, indicating that the device electrode contact was not affected. Note that the

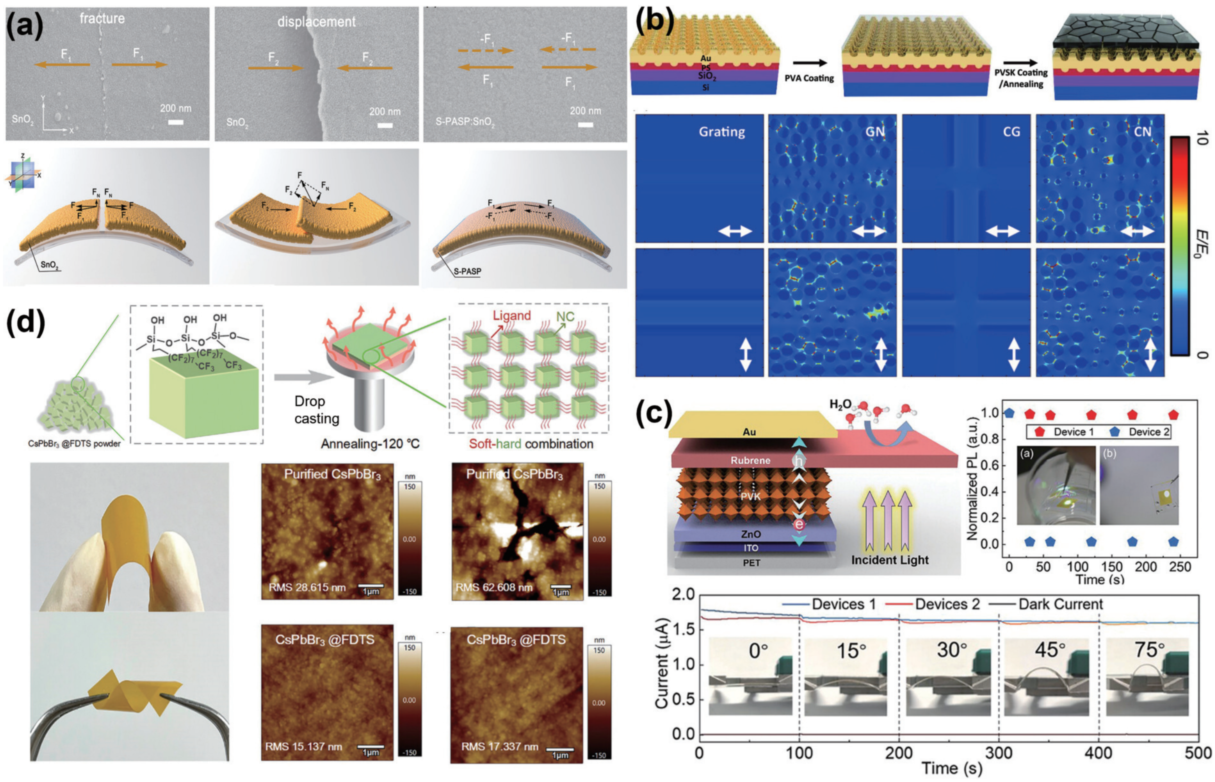

Fig. 5. (Color online) Structurally optimized FPPDs (a) SEM images and mechanical models of pristine SnO_2 and S-PASP: SnO_2. Reproduced with permission from Ref. [72]. Copyright (2023) American Chemical Society. (b) Schematic diagram of the fabrication process and electric field of different plasma structures for x (top) and y (bottom) polarized light. Reproduced with permission from Ref. [74]. (c) Device structure and stability of photodetector with Rubrene protection layer. Reproduced with permission from Ref. [78]. Copyright 2023 Wiley-VCH. (d) Schematic illustration and mechanical properties of the $CsPbBr_3$ films with combined soft-hard structure. Reproduced with permission from Ref. [79].

hydrophobic PMMA polymer coating, not the encapsulated nanocrystals, is what essentially determines the stability of the device.

Since the flexibility of materials can be significantly improved when the scale is reduced to the nanoscale, flexible photoelectric detection can be achieved by fabricating ultra-thin monocrystals and regulated orientation of low-dimensional perovskites[68]. The 20 nm ultra-thin perovskite monocrystal with a high degree of flexibility was grown by the quasi-static solution method in Fig. 4(c), and the photocurrent and dark current of the devices didn't change significantly after different bending processes, indicating that the device has strong bending stability[69]. The highly ordered array of $CsCu_2I_3$ nanowires in Fig. 4(d) was obtained by nanoimprint technology. Due to the substantial structural anisotropy, the device demonstrated exceptional detective performance for linearly polarized light, responding continuously and swiftly to varying polarization angles[70].

3.3. Device structure optimization

The mechanical damage of functional layers and the contact at the interface are the primary causes for the performance attenuation and structural instability of the flexible device. The design of the device structure improves stability through three components: transport layers, intermediate layers, and protective layers, which act on the bottom and upper surfaces of perovskites, respectively. Inorganic semiconductors such as SnO_2 and TiO_2 commonly used in the bottom of devices as electron transport layers face the problems of poor flexibility and high defect density at the interface. The addition of organic salt to the colloidal solution of SnO_2 can increase the crystallinity of SnO_2 and perovskite films through bottom-up regulation, and enhance the interfacial contact[47, 71]. As depicted in Fig. 5(a), the incorporation of the peptide polymer S-PASP to compensate for the stress of the SnO_2 film by stretching and extruding the long chain of the peptide bond avoids the fracture of SnO_2[72].

Covering the upper surface of perovskite with metallic nanoparticles through the plasma enhancement effect to boost the performance and stability of the device is widely used in flexible photoconductors. Zhang *et al.* raised the responsivity and moisture stability of self-driving flexible photodetectors by utilizing the synergistic effect of Ag nanoparticles and F68 polymers[73]. Lee *et al.* reported a hierarchical plasmonic nanostructure by comparing four electrode structures, namely grating, grating with nanoposts (GN), cross-nanograting (CG), and crossing-nanograting with nanoposts (CN) patterns as displayed in Fig. 5(b)[74]. By calculating the electric field increase and far-field scattering of different nanopatterns, it was reasonably inferred that the enhancement of photodetector performance was due to the plasma amplification effect caused by plasmon resonance. The electric field was significantly enhanced between the nanoposts in the GN and CN patterns compared to the grating and CG patterns, which was confirmed by the amplifying field enhancements. The flexible photodetector array fabricated based on the CN pattern exhibited stable and consistent photocurrent and dark current, after 1000 bending cycles with a bending radius of 22 to 6 mm. Another possible working mechanism of metal nanolayer modification is that the Ag nanolayer plays the role of cleaning and passivation of the perovskite surface and also acts as an electron transfer bridge whose working function matches the conduction band energy level of perovskite[75]. The Ag nanolayer-coated $CsPbBr_3$ nanowire photodetector had great stability in an unpackaged, 20%–50% humidity environment. The photocurrent remained 92.5% of the initial value after the cyclic switching test, and had no significant loss after bending at an angle of 0 to 90 degrees.

Before commercial deployment, the devices need to be packaged to isolate the device from the air. However, the mechanical stability of the device may be either negatively or positively impacted by the common packaging technology[76, 77]. In order to avoid the harm of the packaging layer to the device, it is beneficial to explore the top functional layer material with the effect of encapsulation, which also helps improve the features and water resistance of the device. Rubrene films were fabricated through physical vapor deposition, which acted as both a hole transport layer and a protective layer[78]. As displayed in Fig. 5(c), the photoluminescent intensity of Rubrene-protected device 1 was almost unchanged when immersed in water, while the device 2 degraded rapidly in less than 1 m. Rubrene-based optoelectronic devices exhibited excellent self-powered photoelectric detection and enhanced mechanical stability. The photocurrent of the photodetector remained above 90% of the original value at different bending angles, which showed stable and sensitive detection during bending. Additionally, the formation of passivation and end-capping layer on the surface of perovskites with appropriate end-capping agents can repair defects, fix the lattice, and isolate water, becoming an impressive means to improve the flexibility and long-term stability of flexible devices. The photosensitive layer, made stable and flexible by using a rigid-flex structure, incorporated perfluorodecyltrichlorosilane (FDTS) as an end-capping ligand and passivator for $CsPbBr_3$, and it exhibited excellent resistance to bending strain (Fig. 5(d))[79]. The formation of elastic films based on rigid-flex bonding was attributed to residual Si–OH groups on the surface of perovskite, which could induce crystals to pack tightly and generate cross-links. After twisting and bending processes, the morphology of the initial $CsPbBr_3$ film changed, showing clear cracks and an increase in roughness from 28.615 to 62.608 nm. In comparison, the surface of the FDTS-modified films was uniformly packed and barely changed whose roughness of 17.337 nm indicated greater resistance to deformation.

Due to the susceptibility of perovskites to external issues, the exploration of innovative material compositions and fabrication technologies to obtain high-quality, phase-pure perovskite materials is essential for advanced and reliable applications. The primary approaches for raising stability include additive engineering, low-dimensional crystal construction, and device structure design, which can be employed in concert with one another. In addition, the modulation of external conditions, such as electric field, can regulate the phase transition and ion migration, thereby reducing the dark current and increasing the response speed[80].

4. Applications of flexible perovskite photodetectors

FPPDs are transforming various industries with their applications ranging from advanced imaging systems to health monitoring. In imaging, their ability to conform to curved surfaces enhances the design and functionality of cameras and surveillance systems. For health monitoring, FPPDs are integrated into wearable devices to record vital signs like heart rate and blood oxygen levels, offering continuous health data in a non-invasive manner. Their versatility and high performance make them invaluable in developing more responsive and adaptive technology across fields. The following sections will comprehensively introduce the typical applications of flexible perovskite photodetectors in three fields: imaging, health monitoring, and optical communication.

4.1. Optical imaging systems

In recent years, flexible photodetectors have made major breakthroughs in the application of wearable smart sensors and bionic electronic ophthalmic devices due to their stretchability and wide-angle detective capabilities[11, 17]. With the pursuit of flexible photoelectric imaging systems for high performance, long-term stability, and portability, FPPDs are developing toward array, large area, and fine controllability. Wang *et al.* developed flexible photodetectors arrays by SiO_2-assisted hydrophilic and hydrophobic treatment to revamp the lithography process, which exhibited excellent optoelectronic performance and stability, and realized optical trajectory tracking and visible light imaging applications[81]. Mastria *et al.* fabricated nanoscale 2D perovskite photodetectors using electron beam lithography, and subwavelength pixels sized less than 100 nm (Fig. 6(a))[82]. Irradiated with photons with wavelengths five times larger than their geometric size, nano-pixel arrays displayed proportionally large photocurrents as exhibited in Fig. 6(b), indicating reliable high-definition imaging applications. In addition, the interfacial layer at the bottom or top of perovskites has been investigated to improve film quality and interface contact, thereby increasing operating life and performance of the devices[83, 84].

Color recognition in visual perception generally relies on large, high-cost, and complex processes with limited applications. The large-surface, low-cost, and flexible compatibility of perovskites point to a promising direction for high-performance and lightweight color recognition and show broad prospects in the treatment of color vision deficiency. Fu *et al.* fabricated perovskite microwire arrays with tunable bandgap and gradient distribution by capillary bridge assembly method and obtained a high-performance integrated color recognition device[85]. Fig. 6(c) shows the micro-line array integrated photodetector and the result of visible light detection. The photocurrent curves of 23 separated photodetectors were monitored under various illumination wavelengths varying from 400 to 760 nm and then correlated with response ranges based on diverse gradient distribution along the length of the array using a computational algorithm. The spectra reconstructed are well matched to the corresponding ideal spectra of commercial instruments, enabling the reconstruction of monochromatic light and broadband white light at wavelengths of 400 to 650 nm. Devices integrated on flexible substrates showed no significant degradation in performance after bending cycling testing (Fig. 6(d)).

FPPDs can operate in diverse morphologies due to their ability to bend, which gives them specific stereo-vision function. Ji *et al.* used the convex FPPD as the image sensor, com-

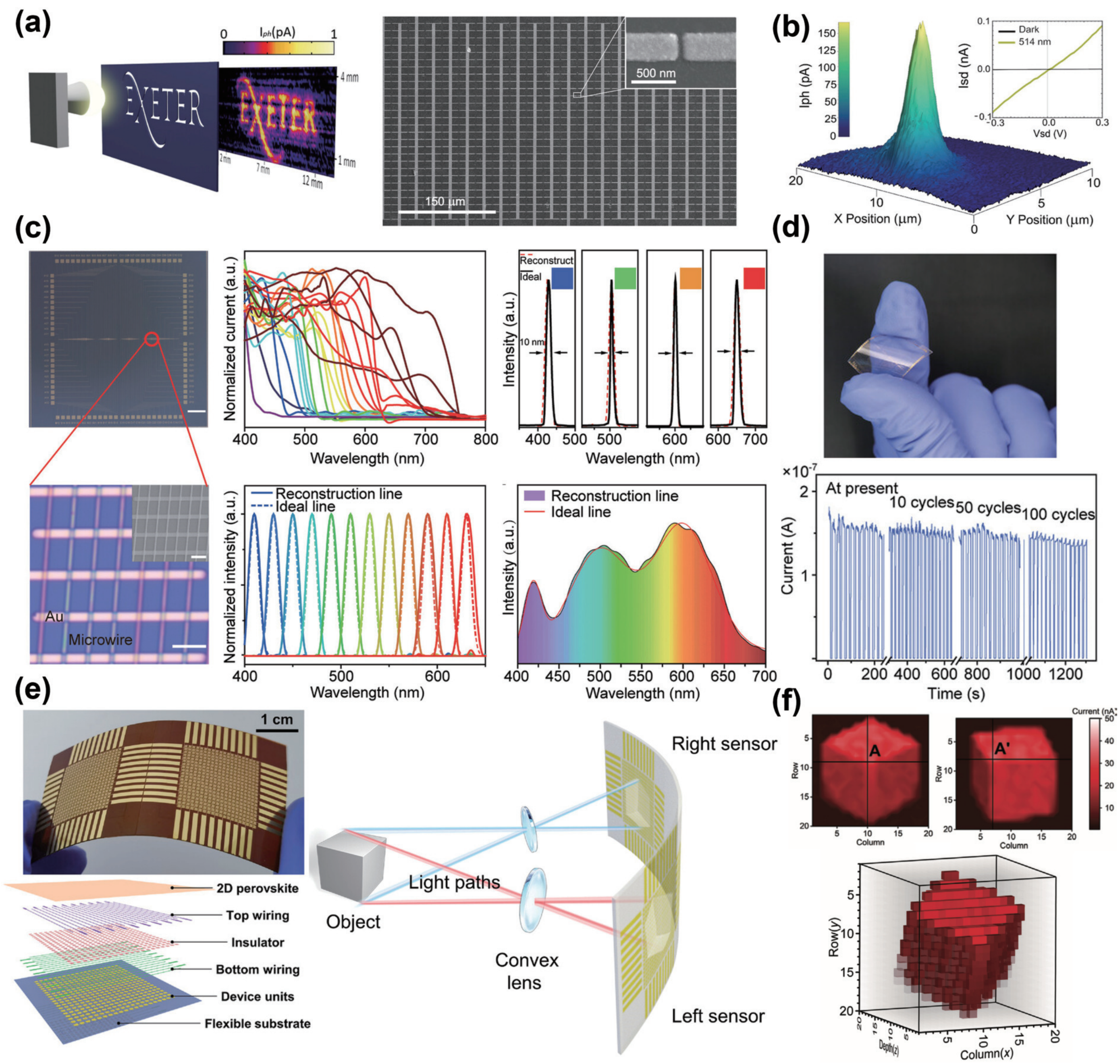

Fig. 6. (Color online) Optical imaging applications of FPPDs. (a) Schematic diagram of the imaging process and SEM image of the photodetector pixel array. (b) Image of the 514 nm laser beam shape. (a) and (b) are reproduced with permission from Ref [82]. (c) Photograph and simulated reconstruction spectrum of the miniaturized spectrometer. (d) Photograph and bending test of the flexible color cognition device. (c) and (d) are reproduced with permission from Ref. [85]. Copyright 2023 Wiley-VCH. (e) Optical photograph and schematic diagram of the imaging sensor. (f) 3D imaging result of a cube. (e) and (f) are reproduced with permission from Ref. [87]. Copyright 2023 Wiley-VCH.

bined with the imaging algorithm, to construct an FPPD camera, which possessed the advantages of a wide-angle field of vision, low image distortion, and high resolution[86]. Inspired by binocular stereo vision, Yan *et al.* composed two flexible perovskite photodetectors to reconstruct the three-dimensional shape by collecting projection images in two directions (Fig. 6(e))[87]. Fig. 6(f) illustrates the procedure for fusing two 2D projected current-mapped images of a cube into a three-dimensional vision.

4.2. Environment and health monitoring sensors

The application of perovskite photodetectors in health monitoring is mainly focused on ultraviolet (UV) detection and infrared heart rate monitoring. Due to the tunable bandgap and self-power response, perovskite photodetector is a potential UV sensor that can avoid long-term UV exposure to the human body, including sunburn and skin diseases. Wearable wristbands can be fabricated by combining flexible photodetectors with commercial integrated circuit technology and flexible printed circuit boards as shown in Fig. 7(a), which offers round-the-clock UV monitoring, signal analysis, and wireless communication (Fig. 7(b))[88]. The UV-sensor wristband based on photochromic perovskite nanocrystals can directly reflect the dosage of solar ultraviolet light through the change of fluorescence color and intensity, which shows the application prospect of visual ultraviolet dosimeter[89]. Flexible UV monitoring devices in solar blinds also demonstrate potential for flame detection and warning capabilities. In Fig. 7(c), the eight curved photodetector arrays were designed into a hemispherical structure using a simple origami method, and the current of other pixels varied differently when the flame was close to A5 pixel. This facilitated flame signal detection and localization at angles from 0° to 180° (Fig. 7(d))[90].

In terms of human-body health monitoring, flexible photodetectors combined with light sources can quantify the pul-

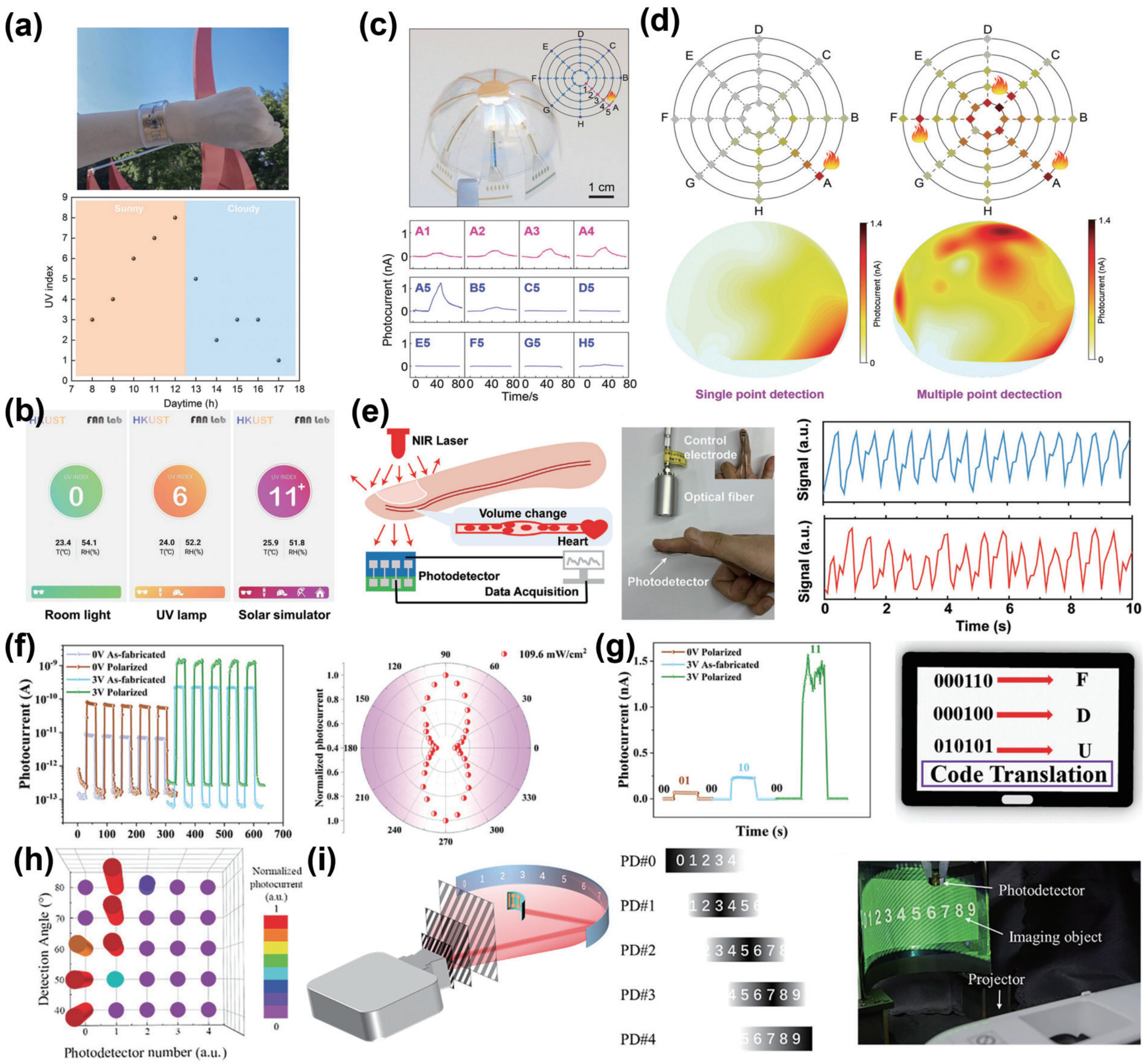

Fig. 7. (Color online) Health monitoring applications of FPPDs. (a) Photograph and round-the-clock UV monitoring of the wearable UV monitor wristband. (b) UV index measured under different light sources. (a) and (b) are reproduced with permission from Ref. [88]. Copyright 2022, Elsevier. (c) Photograph of curved photodetectors array attached on the hemisphere support and current variation of pixels with the flame close to the A5 pixel. (d) Current distribution of photodetectors array under single and multiple flame irradiation. (c) and (d) are reproduced with permission from Ref. [90]. Copyright 2023 Wiley-VCH. (e) Schematic diagram, photograph and heart rate results of photoplethysmography test of rigid (blue) and flexible (red) $FASnI_3$-CNI photodetectors. Reproduced with permission from Ref. [92]. Copyright 2024 Wiley-VCH. (f) *I*–*t* curve tests and polar plot of normalized angle-resolved photocurrents of photodetectors. (g) Correspondence between optical signals and binary digits and binary code conversion. (f) and (g) are reproduced with permission from Ref. [98]. Copyright 2023 Wiley-VCH. (h) 3D histogram of normalized photocurrent of each photodetector under different incident angles. (i) Schematic diagram and photograph of the spatial imaging system. (h) and (i) are reproduced with permission from Ref. [99]. Copyright 2023 Wiley-VCH.

satile state and pulse wave of blood vessels by detecting the damping light signal reflected and absorbed by blood vessels and tissues, to diagnose and prevent certain diseases early. To make the detector fit comfortably on the pads of fingers, Wu *et al*. used a three-dimensional wrinkle-serpentine wire electrical interconnection to construct a flexible sensor that was used to measure limb swelling and estimate blood oxygen saturation[91]. Due to the close contact between wearables and the human skin, safety is another primary consideration. Liu *et al*. constructed a lead-free $FASnI_3$-based flexible photodetector by additive engineering, with a detectivity of 9.12×10^{12} Jones and a response time of 3.91 μs, which was capable of monitoring the heart rate in real time under weak light without bias pressure (Fig. 7(e))[92]. The flexible photodetector exhibited comparable heart rate monitoring results to the rigid device, demonstrating tremendous potential of lead-free perovskites for wearable health monitoring. In addition, the combination of photodetector and pressure sensor to detect light and human motions simultaneously further expands the application of FPPDs in multifunctional electronic skin[93].

4.3. Optical communication

Perovskite materials provide diverse application prospects in multiple components of optical communication such as signal transmission, information storage, and encryption, owing to their exceptional optoelectronic features and

Table 1. Summary of performance parameters and stability of flexible photodetectors.

Device Structure	I_{on}/I_{off}	*R* (A/W)	*D** (Jones)	*E*	Response time	Voltage (V)	Respond wavelength	Long-term stability	Flexible stability (angle/radius, cycles)	Ref
PET/$CH_3NH_3PbBr_3$/Au	200	5600	6.59×10^{11}	–	$\tau_{rise} = 3.2\ \mu s$ $\tau_{decay} = 9.2\ \mu s$	1	540	–	11 mm, 1000 cycles	[69]
PET/$MAPbI_3$-$MAPbBr_3$/Au	2.1×10^5	233	6.98×10^{13}	44 413%	$\tau_{rise} = 3.9$ ms $\tau_{decay} = 2.0$ ms	0	650	95.8% after 115 d; 88.2% after 391 d	83.3%, 150°, 3000 cycles	[43]
PEN/$FAPbI_3$/PCBM/Au	–	11.32	9.4×10^{11}	–	$\tau_{rise} = 61$ ms $\tau_{decay} = 134$ ms	5	650	> 90% after 8–9 h	75%, 180°, 1000 cycles	[62]
PET/ITO/ZnO/$CsPbBr_3$/Rubrene/Au	17 700	0.124	2.61×10^{13}	–	$\tau_{rise} = 79.4\ \mu s$ $\tau_{decay} = 207.6\ \mu s$	0	465	97% after drying	75°, 1000 cycles	[67]
PET/ITO/PEDOT:PSS/(APP)PbI_3/γ-$CsPbI_3$/C_{60}/BCP/Cu	–	–	~10^{12}	2377%	–	−0.6	532	95.2% for 1500 h	>90%, 4.5 mm, 20 000 cycles	[41]
ITO/PEDOT:PSS/$FA_{0.8}PEA_{0.2}SnI_3$/PCBM/BCP/Ag	–	0.262	2.3×10^{11}	–	$\tau_{rise} = 27.7\ \mu s$ $\tau_{decay} = 20.4\ \mu s$	0	NIR	From 9.3 to 1.1 nA after continuous 13 500 test cycles for 7.5 h in air	2 mm, 10 000 cycles	[56]
PET/$(F\text{-}PEA)_2PbI_3$/Au	–	1120	5.5×10^{17}	–	–	20	405	–	3.5 mm, 1000 cycles	[82]
PET/$BA_2MA_2Pb_3Br_{10}$/Au	3.7×10^3	0.92	1.02×10^{11}	310%	–	3	410	98.2% over 100 cycles	92.3%, 10°, 5000 cycles	[98]
PET/ITO/Cr/Au/$(PMA)_2FAPb_2I_7$/Au NPs/FACl	$>5 \times 10^3$	4.7	6.3×10^{12}	–	–	2	450	90% after more than 40 d	70°, 5000 cycles	[81]
PET/ITO/PEDOT:PSS/$FASnI_3$-CNI/PCBM/C_{60}/PEN-Br/Ag	~10^5	0.37	9.1×10^{12}	71.7% @600 nm	$\tau_{rise} = 4.17\ \mu s$ $\tau_{decay} = 3.91\ \mu s$	0	785	20 000 s	–	[92]
PET/ITO/Au/SiO_2/PEDOT:PSS/$(BA)_2FAPb_2I_7$-FACl/C8BTBT	–	2.3	3.2×10^{12}	–	$\tau_{rise} = 9.74\ \mu s$ $\tau_{decay} = 8.91\ \mu s$	2	405	88% after more than 1000 h	50°, 1000 cycles	[97]
Au-Ti/$MAPbI_3$-CNC/Ti-Au	–	0.23	–	42.2%	$\tau_{rise} = 600\ \mu s$ $\tau_{decay} = 709\ \mu s$	5	650	65% after 30 d	87%, 2 mm, 1000 cycles	[58]
ITO/SnO_2/$MAPbCl_3$/PTAA/Au	–	0.063	–	–	$\tau_{rise} = 3.91$ ms $\tau_{decay} = 4.55$ ms	0	395	Unchanged after 500 h	80%, 7 mm, 2500 cycles	[88]
PET/Au/SiO_2/OTS/$CsCu_2I_3$	9.68	62	1.4×10^{11}	–	$\tau_{rise} = 13$ ms $\tau_{decay} = 19$ ms	2	254	8 h	30°, 500 cycles	[90]
ITO/$CsPbBr_3$/PEDOT: PSS/PDMS	168.7	8.1×10^{-5}	4.8×10^{11}	–	$\tau_{rise} = 0.176$ s $\tau_{decay} = 0.09$ s	10	NIR	–	1000 cycles	[93]

potential flexibility[3, 94, 95]. High sensitivity and response speed are requisite for the photodetectors to receive signals in an optical communication system, which emphasizes the quality of photoactive materials, carrier transmission as well as stability[96]. Wang *et al.* combined additive passivation and nano-Au plasma enhancement to improve the response and stability of the device, and then integrated into the optical communication system to achieve efficient signal transmission[97]. Zhang *et al.* integrated ferroelectric properties into the design of flexible perovskite photodetectors[98]. In addition to greatly enhancing the photoelectric effect, altering the width of the two-dimensional perovskite quantum well allowed for the realization of polarization control optoelectronic performance (Fig. 7(f)). The correspondence between the optical signal and the binary before and after polarization was used to realize the application of flexible decoding as shown in Fig. 7(g). Moreover, given that the photocurrent of linear perovskite is correlated with the incident angle (Fig. 7(h)), spatial encrypted imaging can be achieved by encoding the incident angle into a password and selectively displaying the picture data as indicated in Fig. 7(i)[99].

Although phase separation resulting from ion migration is an important cause of the hysteresis and degradation of perovskite devices, the utilization of ion migration to design computational memristors with dual control of electrons and photons is expected to promote the development of integrated sensing and storage computing technology[100].

According to the above applications, FPPDs have been widely employed in optoelectronic fields such as optical imaging, health monitoring, and optical communication. Table 1 summarizes the critical parameters and stability of the currently reported FPPDs. It is expected that the light detection performance, operational stability, and environmental compatibility of the FPPD will be enhanced, further driving its practicability.

5. Conclusion

Perovskites, the promising materials in optoelectronics, are poised to address the limitations of traditional inorganic photodetectors in terms of rigidity and organic photodetectors in response speed, heralding significant advancements in flexible photodetectors. This review summarizes recent progress in FPPDs, focusing on device architectures, stability enhancement strategies, and advanced applications. The distinct types of devices—photoconductors, photodiodes, and phototransistors—offer specific benefits suitable for various applications. Photoconductors are notable for their high responsivity and suitability for array configurations, photodiodes offer rapid response without the need for external voltage, and phototransistors provide high gain and integration. The structure of photodetectors, along with the composition and morphology of perovskite, are crucial in determining the performance and stability of FPPDs.

The long-term stability and widespread application of perovskite materials are impeded by the existence of defects and traps in their bulk and interfaces. Defects cause disruptions in charge transport and hasten the deterioration of materials, especially in flexible perovskite devices. Perovskite devices employ passivation strategies for buried interfaces, bulk, upper interfaces, and bulk-interfaces, which are typically accomplished through doping, single crystals preparation, surface modification, and intermediate layers. Beyond high-quality perovskite materials, excellent interfacial contact, and effective encapsulation, devices that feature intrinsic flexibility and self-healing capabilities show vast potential for future applications.

FPPDs find applications in imaging, monitoring, and communication, demonstrating their versatility through high performance, adaptability, and long-term stability. Further development of innovative processing techniques for depositing various perovskite morphologies on different flexible substrates—such as organic polymers, paper, textiles, and fibers—is essential as commercial applications progress.

While many FPPDs have demonstrated the ability to maintain performance through bending cycles, they often exhibit cracks and performance degradation after extensive bending at multiple angles, indicating that further improvements in mechanical properties are necessary for commercial viability. Mechanical damage typically affects all functional layers of the photodetectors, with the photosensitive layer, the electron transport layer made of inorganic metal oxides, and the interfaces being particularly vulnerable. The integration of organic elastomers acts like a cushion, akin to springs, which can mitigate and repair mechanical damage during deformation, thus becoming a crucial strategy to enhance the operational stability of flexible devices.

Interface passivation is another key approach, effectively minimizing interface defects and preventing mechanical damage that can arise from stress concentrations at these defects. Although many additives have been investigated to passivate defects and promote crystal quality and stability, the underlying mechanisms remain inadequately explored. Continued research into photoactive materials that can maintain stability under operational conditions is highly anticipated.

Environmental stability presents another significant challenge to the commercialization of perovskite devices. Techniques such as component engineering and additive engineering are essential to improving the intrinsic stability of perovskites in air, and encapsulation plays a critical role as well. However, research into protective layers is still limited, and investigating upper functional layers capable of air insulation is promising. In conclusion, as advancements in compatibility and stability progress, FPPDs are increasingly able to meet the growing demands of the field of flexible electronics.

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