Review

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Posted Date: 20 August 2024

doi: 10.20944/preprints202408.1371.v1

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Application of Metal Halide Perovskite in Internet of Things

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Abstract: The Internet of Things (IoT) technology connects the real world and the network world by integrating sensors and internet technology, which has greatly changed people's lifestyles, showing its broad application prospects. However, traditional materials for the sensors and power components used in IoT limit its development to high-precision detection, long-term endurance, and multi-scenario applications. Metal halide perovskite, with the unique advantages such as excellent photoelectric properties, adjustable bandgap, flexibility, and mild process, exhibiting enormous potential to meet the requirements for IoT development. This paper provides a comprehensive review of metal halide perovskites' application in sensors and energy supply modules within IoT systems. Advances on perovskite-based sensors were discussed as to gas, humidity, photoelectric, and optical sensors. The application of indoor photovoltaics based on perovskite in IoT systems were also discussed. At last, the application prospects and challenges of perovskite-based devices in IoT are summarized.

Keywords: internet of things; lead halide perovskite; sensor; indoor photovoltaic

1. Introduction

1.1. Basic Concepts of IoT

Internet of Things (IoT) could collect various information about objects in real-time by utilizing sensors and positioning systems. Physical and virtual objects can be seamlessly connected with various network accesses. The term "Internet of Things" was initially proposed in the 1990s by Professor Kevin Ashton [1], a co-founder of the Auto-ID Laboratory at the Massachusetts Institute of Technology (MIT). He introduced this term to describe a system in which the internet is connected to the physical world through ubiquitous sensors. To date, IoT has garnered significant attention and its applications span across multiple fields including medical, management, information technology, agriculture, defense [2–7]. Recently, loT tends to integrate with metaverse technology [8], which serves as an indispensable vehicle for the fourth industrial revolution [9].

1.2. Three-Layer Architecture of IoT

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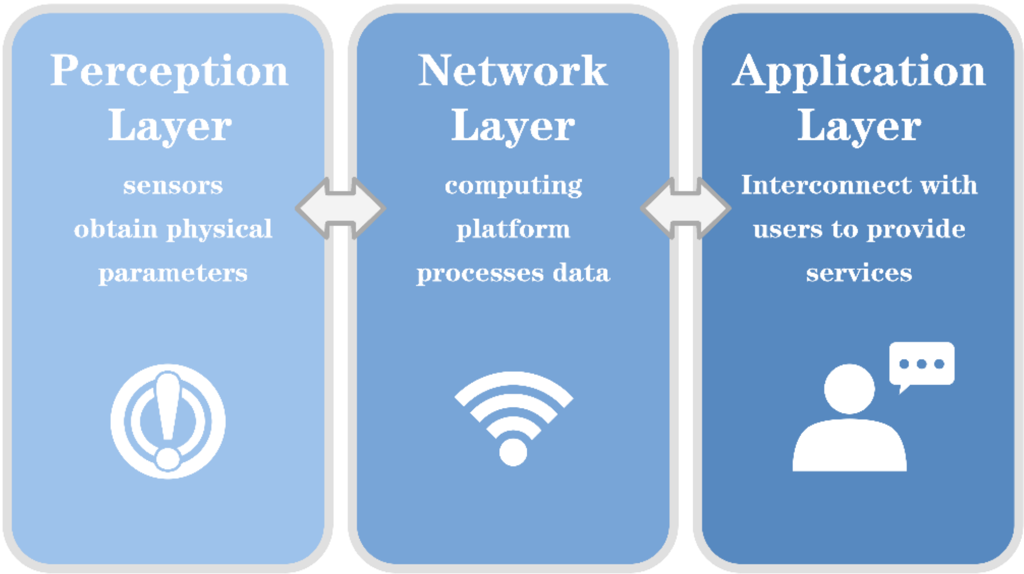

Figure 1. Diagram of the basic structure of the Internet of Things.

IoT is basically consists of three layers: perception layer, network layer, and application layer [10], as shown in Figure 1.

- The perception layer covers various physical devices and sensors to gather physical data from the environment, serving as the source for IoT object identification and information collection;
- The network layer comprises various networks and computing platforms, functioning as the central hub of the entire IoT system. Data collected from the perception layer undergoes further processing in this part;
- The application layer provides specific services to end users, acting as the interface between IoT and users. This layer employs a variety of intelligent technologies to analyze and process data received from perception layers, which is closely integrated with industry requirements

1.3. Development Status and Trend of Perception Layer

LoT connects the physical and internet worlds together by a series of sensors, which determines the upper limit of IoT functionality [11]. Further development depends on enhancing sensor functionality, endurance, and application scope.

In terms of functionality, variety and sensitivity of sensors are paramount. At present, sensors still need further development in sensitivity, working environment, and detection diversity to meet these demands.

Endurance capability is also crucial for ensuring continuous power supply for devices in loT [12], especially for those that are difficult to locate. Presently, most IoT power supply relies on rechargeable batteries or wired power supply system. Though rechargeable batteries can liberate sensors from scenario restrictions, the problem of battery endurance and replacement become particularly prominent when it comes to an IoT system with millions of sensors.

The portability of IoT sensors is a concern as IoT becomes more integrated into daily life with diverse application scope. Many wireless, flexible and wearable sensors have been developed, but they still face problems such as lower sensitivity and stability than traditional devices and higher manufacturing cost [13–15].

It is evident that the development of IoT has raised higher demands for its sensors, energy sources and device portability, which all rest with the research on new materials.

In recent years, metal halide perovskite materials have attracted significant attention in the field of optoelectronics due to their tunable bandgap, excellent optoelectronic properties, low preparation cost, and strong process compatibility. These materials demonstrate enormous potential for development in IoT domain. The tunable bandgap of perovskites enables broad-spectrum

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photoelectric conversion, making them suitable for manufacturing high-sensitivity light sensors. Their unique optical and chemical properties also allow perovskite sensors to accurately measure various environmental parameters. Additionally, perovskite is recognized as an outstanding photovoltaic material with high photoelectric conversion efficiency, which can serve as a soalr cell to provide power supply [16,17]. Furthermore, the flexibility, semi-transparency, and color adjustability of perovskite materials offer greater versatility in shaping sensor and battery designs. In the production process, the solution-based fabrication method of perovskites results in higher compatibility and lower costs for large-scale applications [18–22].

There have been a considerable number of review papers that separately covered perovskite-based gas and humidity sensors, photodetectors, and solar cells [23–25]. However, a comprehensive review focused mainly on the applications of perovskite-based devices in Internet of Things is lacking in the literature. In this review, we summarize the latest progress of perovskite in IoT from its applications in sensors and photovoltaics. First, we introduce some basic concepts about perovskite, especially metal halide perovskite. Then, we summarize the recent progress on some kinds of perovskite-based sensors, including gas, humidity, photoelectric, and optical sensors. Besides, we introduce perovskite solar cells and indoor photovoltaic technology. Despite the considerable advancement in the field, there are several key challenges ahead to face in the further development. Therefore, we have provided a survey of challenges and opportunities in the last section.

2. General Properties of Perovskites

2.1. Concepts

As early as 1839, Gustavus Rose, a mineralogist at the University of Berlin, discovered perovskite in the Ural Mountains of Russia and named the substance after Russian geologist Lev Perovski. Perovskite originally referred only to the material $CaTiO_3$, but now more often refers to substances with the perovskite structure and the formula ABX_3 (A is an organic or inorganic metal ion, B is a metal ion, and X is an oxygen or halogen ion) [25].

2.2. Structure and composition

This article primarily introduces metal halide perovskites (ABX_3), where A generally refers to metals such as Cs or certain organic cations like methylammonium (MA) and formamidinium (FA), while B typically denotes metals such as Pb. Under this premise, monovalent and divalent cations are usually stabilized at the A and B sites respectively. Here, A is situated at the center of the octahedron formed by X, as shown in Figure 2(a), with a coordination number of 12; whereas B is located at the center of the octahedron formed by X, as shown in Figure 2(b), with a coordination number of 6.

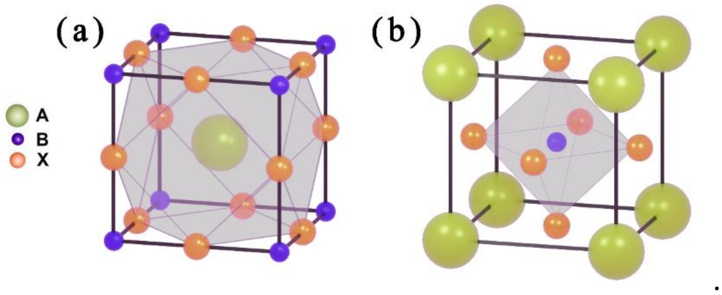

Figure 2. Schematic diagram of perovskite structure: (**a**)coordination number is 12; (**b**)coordination number is 6.

2.3. Properties

Due to the unique structure described above, metal halide perovskites have many special characteristics. Take $MAPbI_3$ for example, when it is exposed to a specific gas environment(e.g., O_2, NH_3, H_2O), gas molecules are able to diffuse inside the perovskite crystal structure and to fill

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reversibly iodine vacancies that are intrinsically present inside the crystals [26]. This phenomenon is called 'trap healing mechanism', which is beneficial for their application in gas and humidity sensors [27,28]. In addition, this material has a suitable bandgap of ~1.55 eV, which matches the wavelength of ~800 nm, making it a competitive light-absorbing material for solar cells and photosensors [24]. The bandgap and spectra of perovskite material can even be adjusted through the modulation of halogen component (I^-, Br^-, Cl^-) within the crystal structure, which greatly broadens the application scope of perovskite [29]. Besides, perovskites also possess some other fascinating properties such as piezoelectricity, a high absorption coefficient, and long charge diffusion length [30,31]. These attractive features make perovskites ideal candidates for sensors and optoelectronic devices in IoT.

3. Perovskite Sensors

With the rapid expansion of IoT, there is a growing demand for high-efficiency and low-energy devices. Against this backdrop, metal halide perovskite sensors with characteristics including excellent gas-sensitivity, humidity sensitivity, photoelectric properties, optical properties, self-powering capability, reversibility, flexibility, and high efficiency are increasingly manifesting their significance within the IoT landscape.

3.1. Gas and Humidity Sensor

Due to perovskite's excellent electronic and ionic conductivity, perovskite gas sensors can detect very small changes even in low gas concentration environments [32,33], and enable efficient sensing at room temperature, which is a enormous advantage for gas sensing [34]. As a contrast, traditional gas sensors, especially metal oxide semiconductor (MOS) sensors, still suffer from partial irreversibility [35] and require an operating temperature above room temperature to ensure that the surface activity can fully react with the target gas, only in this way can sufficiently high responses ultimately be obtained [36,37], which poses challenges for maintaining sensor stability and limit the application scope.

The working principle of perovskite gas sensor is based on the physical or chemical interaction between the sensing material and the target gas. These reactions change the electrical properties of the sensor, such as resistance, capacitance, or conductivity, which depend on the properties of target gases and semiconductor materials (n-type, p-type). In the case of n-type semiconductors, electron depletion regions will appear on the material surface during chemisorption, consequently causing an increase in resistance. While p-type semiconductors demonstrates opposite behavior to resistance changes, because holes are considered to be the charge carriers [23]. Monitoring can be achieved by detecting such changes.

The working principle of perovskite humidity sensor is similar to the gas one. Water molecules can be easily adsorbed by sensor's surface due to their large dipole moment, and affect the materials' properties. Devices made from perovskite were once infamous for failing due to H_2O, which causes unsatisfactory long-term stability. But by taking advantage of perovskite's excessive sensitivity to humidity, it is possible to produce quite good humidity sensors.

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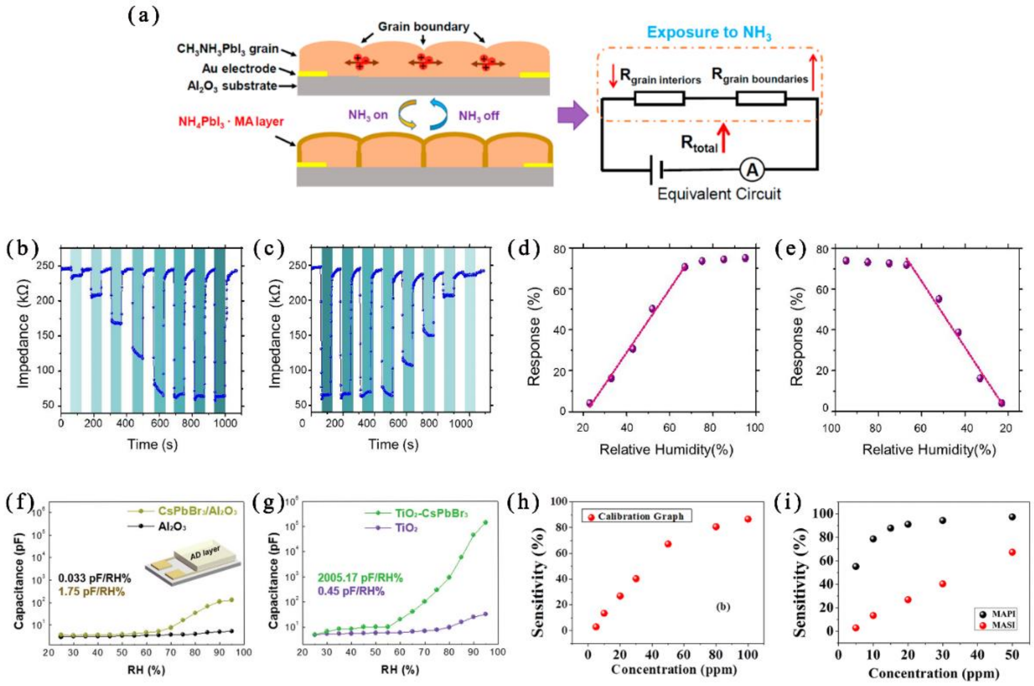

Figure 3. (**a**) Illustration of a NH_3 sensing mechanism in $MAPbI_3$ film [38]; Dynamic impedance response curves versus time with (**b**) gradually increasing RH environments and (**c**) decreasing RH environments; The RH response summary of the sensor at different RH as humidity (**d**) increase and (**e**) decrease gradually [39]; Capacitance variation with different RH values ranging from 25 to 95 RH%: (**f**) Al2O3 and CsPbBr3/Al2O3; (**g**) TiO2 and CsPbBr3/TiO2 [40]; (**h**) the sensitivity of the lead-free halide perovskite-based gas sensor at different NH_3 concentrations; (**i**) comparison of sensitivity between lead halide $MAPbI_3$(MAPI) and lead-free halide $MASnI_3$ (MASI) perovskite NH_3 sensors both grown on a fabric substrate [41].

In 2021, Li et al. [38] proposed a NH_3 sensing mechanism in which the anomalous resistance enhancement is dominated by grain boundaries of perovskites. It is demonstrated that NH_3 molecules can substitute MA^+ cations of $MAPbI_3$ to form the insulating $NH_4PbI_3{\cdot}MA$ intermediate layers onto the surface of crystal grains, thereby resulting in an increase of resistance, as shown in Figure 3(a). Additionally, they constructed an $MAPbI_3$-based gas sensor, and achieved a gas response of 472% toward 30 ppm of NH_3. This study provides guidance for developing high-performance sensing perovskite materials.

In the same year, Wu et al. [39] demonstrated an excellent impedance relative humidity sensor based on all-inorganic halide perovskite $CsPbBr_3$ nanoparticles (NPs) under low working-voltage (20 mV). The $CsPbBr_3$ NPs humidity sensor exhibits fast response and recovery behavior at room temperature. Dynamic impedance response curves versus time with gradually increasing relative humidity (RH) environments and decreasing RH environments are shown in Figure 3(b)-(c). When the sensor switches in different humidity environments, the impedance of the sensor immediately spring back to its original state. As shown in Figure 3(d)-(e), the impedance of the sensor in the saturated region is almost unchanged, and then linearly decreases as the RH decreases to 75 %, illustrating that the humidity sensor can desorb the water molecules in a short time completely. In addition, the $CsPbBr_3$ NPs humidity sensor produces low hysteresis outputs(3%) when measuring different RH levels with upward and downward trends, further demonstrating the good reversibility. This study suggests that humidity sensors made of metal hailde perovskite like $CsPbBr_3$ NPs have great potential in future real-time monitoring applications, especially in IoT.

In 2022, Cho et al. [40,42] first chose all-inorganic metal halide perovskites for the preparation of humidity sensors. By using aerosol deposition method, they successfully compounded $CsPbBr_3$ and $CsPb_2Br_5$ with various traditional humidity-sensitive ceramic materials (Al_2O_3, TiO_2, and $BaTiO_3$)

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together and made a novel capacitive humidity sensor. As shown in Figure 3(f)-(g) (where RH is the relative humidity), $CsPbBr_3$-impregnated humidity sensor shows remarkably high sensitivity. In 2024, Zhang et al. [43] introduced a methylamine gas sensor based on MAPbBr3 and the aggregation-induced emission (AIE) material (S)-OBN-tCz. It's worth noting that the incorporation of AIE material has successfully improved the signal intensity of optical sensors through Förster resonance energy transfer mechanism and passivation effect, thereby effectively enhancing the sensitivity of sensors. These studies show that it is possible to boost the effectiveness and sensitivity of sensors by combining other materials with lead halide perovskite, considering an efficient way to further improve the existing sensors.

In 2024, Maity et al. [41] reported a lead-free halide perovskite-based gas sensor to detect ammonia gas. The sensor uses methylammonium tin iodide ($CH_3NH_3SnI_3$ or $MASnI_3$ or MASI) as the active material. The maximum calibrated sensitivity based on the electrical readout of the sensoris ~85% on exposure to 100 ppm ammonia gas, as shown in Figure 3(h). The sensor can be operated at 2 V bias with an output current of ~2 nA, making ourdevice compatible with low-power e-textile-based wearable gas sensors. Further, the gas-sensing performance of the lead-free halideperovskite-based ammonia sensor has been compared with its lead-based counterpart, as shown in Figure 3(i). Though the lead-free halide perovskite-based gas sensor has a much lower sensitivity, this study shows that it is possible to change the Pb element into other elements to avoid the toxicity of lead so that the sensor can be applied to family life, which lays a foundation for the further application of metal halide perovskite sensors in IoT.

3.2. Photodetector

Photodetectors (PDs) operate on the basis of the transition of electrons from the lower energy state to the higher energy state under photonic illumination. At present, PDs can be divided into photoconductive (PC) mode and photovoltaic (PV) mode two kinds. PC mode detectors identify the light signal by detecting the change of resistance across the photoactive material under illumination. In contrast, PV-type PDs utilize the built-in electric field in heterojunction or Schottky junctions to separate the photogenerated electron–hole pairs. Thus, the need for an external bias is omitted, so the device can become a self-powered PD [24]. Figure 4(a)-(b) illustrates the charge separation under the PV effects in heterojunction and schottky junction.

The most common photodetector is made from inorganic semiconductor material. However, the slow response times observed in these devices severely restrict their application in high-speed devices [44]. Based on these issues, the application of metal halide perovskite materials in the field of photodetector has attracted attention. Metal halide perovskite's main inherent defects are shallow defects that do not affect the rapid response of optoelectronic sensors, so utilizing metal halide perovskite in photodetector can effectively suppress dark current, increase linear dynamic range, achieve high detection rates and fast responses [45–47].

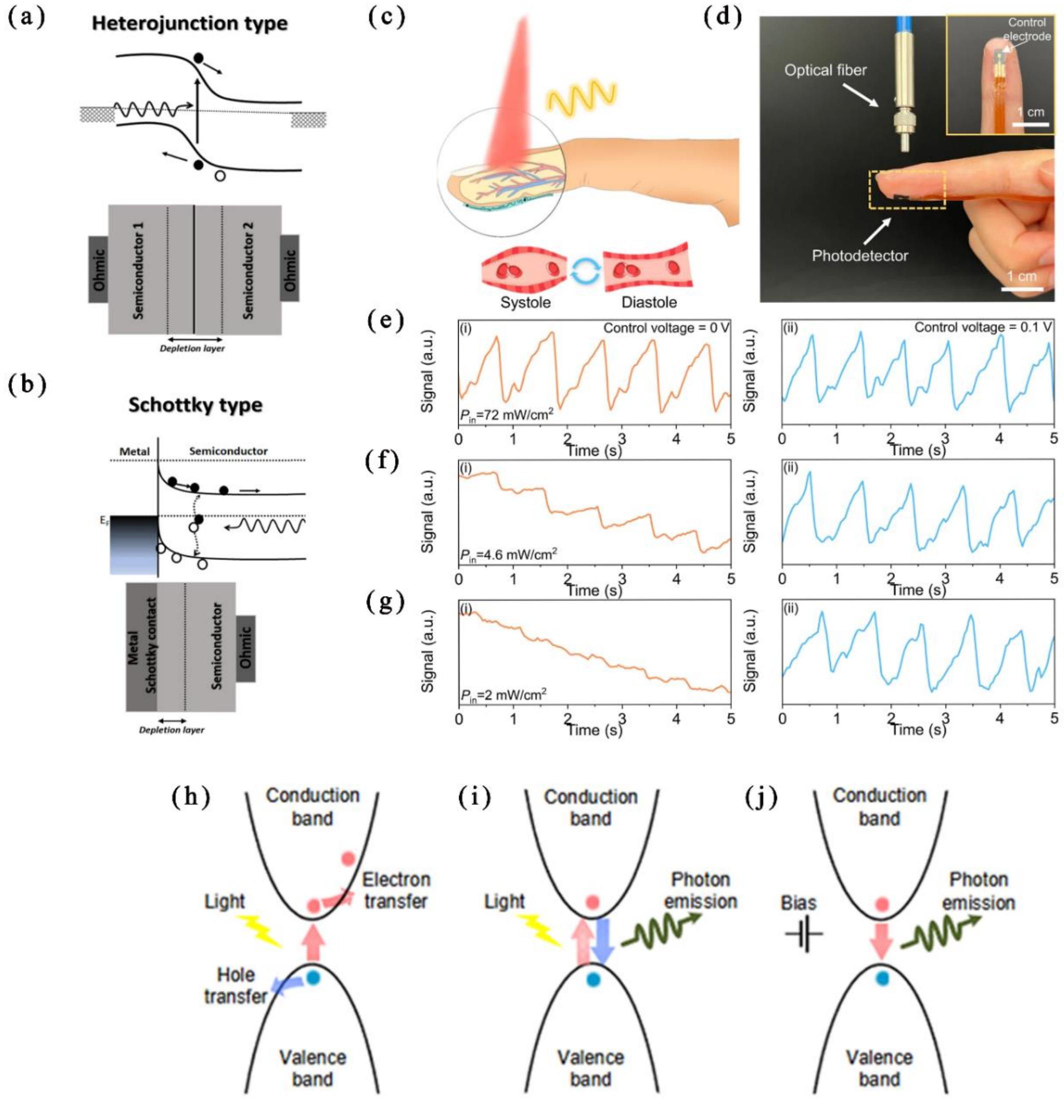

Figure 4. Schematic diagrams of working principle of self-powered PDs in PV mode: (**a**) heterojunction type: (**b**) Schottky type [24]; Application of the FPDs for blood pulse signal detection: (**c**) schematic diagram of the working principle of the photoplethysmography test: volumetric changes in the blood vessels modulate the transmitted light intensity; (**d**) photograph of the FPD attached on finger pulp as photoplethysmography sensor for recording blood pulse signal. An 800 nm light beam is generated from the optical fiber and reaches the FPD through the finger. Inset shows the top-view photograph of FPD connected with a flexible printed circuit board; (**e**)–(**g**) comparison of photoplethysmography signals detected by the FPD under different incident light intensities (72, 4.6, and 2 mW/cm^2) when the control electrode was applied with 0 and 0.1 V. The calculated blood pulse frequency was 67 beats per minute [48]; (**h**) photoelectric conversion mechanism; (**i**) all-optical conversion mechanism; (**j**) electro-optical conversion mechanism of perovskite [49].

In 2023, Algadi et al. [50] produced a self-powered and high-performance vertical type heterojunction photodetector based on solution-processed NGQDs/ $CsPbBr_3$. The PD exhibited high-performance with a light current (257.71 nA), an on/off ratio (670), responsivity (R=3.21 A/W), specific detectivity (D*=2.9× 1012 J), and an external quantum efficiency (EQE=270%) under illumination of light source with a wavelength of 520 nm and power intensity of 0.8 mW/cm^2 at bias voltage of 3 V, and is confirmed to operate without an external bias voltage demonstrating the obvious photovoltaic characteristics of the device at 0 V. Miao et al. [51] prepared a compact, uniform, pinhole-free, and highly crystallized 2D–3D gradient perovskite film($MAPbI_3$) by hot-casting method, and produced a photodetector with an extremely low dark current density (2.3 × 10^{-11} A/cm^2), large specific detectivity (1.22 × 1014 Jones) at 455 nm, ultra-fast response time (5.5/4.7 μs) and ultra-high on/off ratio of 108. These studies indicate metal halide perovskite's great potential for high-efficiency photodetector without the voltage bias.

In 2024, Tang et al. [48] proposed an electrical field modulation strategy to significantly reduce the dark current of metal halide perovskites-based($MAPbI_3$) flexible photodetector more than 1000 times (from ~5 nA to ~5 pA). Meanwhile, ion migration in metal halide perovskites is effectively suppressed, and the photodetector shows a long-term continuous operational stability (~8000 s) with low signal drift (~4.2 × 10−4 pA per second) and ultralow dark current drift (~1.3 × 10−5 pA per second). Benefitting from the excellent light-sensing performance, flexible photodectors (FPDs) prepared by this strategy can obtain high-fidelity blood pulse waveform under low incident light intensity (2 mW/cm^2), as shown in Figure 4(c)-(g), which is critical for the application in low-power consumption wearable electronics.This work offers a universal strategy to improve the performance of metal halide perovskites for wearable flexible photodetectors, showing the application prospect of metal halide perovskite in flexible devices of IoT.

3.3. Optical Conversion Sensor

Perovskite materials have excellent photovoltaic, electro-optical, and all-optical conversion properties compared to traditional sensors. Therefore, various types of perovskite optical conversion sensors can be developed with these properties.

The mechanism of photo/bias regulating-charge carrier (electron/hole) generation and transfer is shown in Figure 4h–j. With good optoelectronic properties, metal halide perovskite can capture incident light and generate excitons (hole and electron pairs). These excitons can overcome the exciton binding energy, and separate into free electrons and holes, which are referred to as 'photoelectric conversion', as shown in Figure 4(h). Excited by the external bias voltage, the electrons in the higher energy state of the conduction band recombine with the holes in the valence band and emit fluorescence photon, which are called 'electro-optical conversion', as shown in Figure 4(i). Meanwhile, when metal halide perovskite is illuminated, all-optical conversion occurs, as shown in Figure 4(j). Under an overloaded external bias and illumination, the ions in the perovskite (I^-, Br^-, Pb^{2+}, MA^+) and electrode (Ag^+) migrate out of the ABX_3 perovskite structure, resulting in defect band levels, and the resistance changes subsequently [49].

In 2020, Chen et al. [52] engineered a superhydrophilic $CsPbBr_3$@polystyrene/polyacrylamide all-optical conversion sensor, which is capable of quantifying Fe^{3+} levels in human blood. Beyond Fe^{3+}, these sensors can exhibit sensitivity towards various metabolic substances present in human body, such as urea, chloride ions, and iodide ions. Wang et al. [53] utilized the photo-luminescence property of $CsPbBr_3$ quantum dots and the hydrophobicity of boron nitride to construct a hydrophobic fluorescence sensor for tetracycline identification. The linear detection range of the sensor was 0-0.44 mg·L^{-1}, and the detection limit was as low as 6.5 ng·mL^{-1}. Xiang et al. [54] utilized the property that $CsPbBr_3$ easily degrades in the presence of water to develop a highly humidity-sensitive photo-luminescence sensor, which can detect the water content in traditional Chinese medicine. The sensor showed a good linear relationship within the relative humidity range of 33%-98%, and the relative humidity detection limit was 12%.

These studies show that it is very promising to develop various perovskite sensors by using its optical properties

3.4. Nanogenerator

Besides photodetectors that are themselves self-powered, there is another way to make sensors which lack of this ability self-powered. The nanogenerator (NG) is a new technique, first proposed by Wang et al. [55] in 2007, that utilizes mechanical and thermal energies produced by human body motion and then converts into electrical energy. In 2019, Wang et al. [56]predicted and proposed the friction volt effect for the first time. In 2020, Zhang et al. [57]experimentally verified this phenomenon and defined the 'friction volt effect' as the generation of direct current at the interface between a metal/semiconductor and another semiconductor due to friction. After that, researchers discovered that by using the 'friction volt effect' to convert mechanical energy into electrical energy, which makes self-powered sensors possible [58]. Perovskite materials have excellent semiconductor properties, they can generate a direct current signal and separate the photoelectric electrons and holes by forming a heterojunction [59]. Therefore, perovskite combines the photoabsorption characteristics and piezoelectric/friction effect, can be suitable candidates for self-powered sensors [60].

In 2019, Sultana et al. [61] a developed piezoelectric–pyroelectric nanogenerator (PPNG) based on $MAPBI_3$-polyvinylidene fluoride material, which is able to harvest mechanical and thermal energies. During the application of a periodic compressive contact force at a frequency of 4 Hz, an output voltage of ~220 mV is generated. The PPNG has a piezoelectric coefficient (d33) of ~19.7 pC/N coupled with a high durability (60000 cycles) and quick response time (~1 ms). The maximum generated output power density (~0.8 mW/m^2) is sufficient to charge up a variety of capacitors.

Subsequent research on NGs focused on improving the band alignment, carrier recombination, and mechanical wear between interfaces [62]. Though integration of NGs with sensor devices is always challenging, further development of NG-based self-powered sensors is extremely attractive.

4. Perovskite Solar Cells and Indoor Photovoltaics

4.1. Research Progress

The primary power source for wireless sensor devices in IoT is mainly rechargeable batteries. However, these batteries require regular maintenance and replacement, and pose certain environmental hazards, which are not conducive to green and sustainable practices. Therefore, the technology of harvesting and collecting energy from natural sources such as light, heat, and magnetism has garnered attention from researchers. Among these technologies, solar cell technology stands out as it enables low-energy wireless portable devices to sustain their own power supply without the need for replacement or maintenance.

The development of solar cells can be categorized into three generations: silicon-based solar cells (first generation), thin-film solar cells (second generation), and various new type solar cells with higher efficiency (third generation). Compared to the first two generations, third-generation solar cells offer lower costs and higher efficiency while experiencing rapid development. As depicted in Figure 5(b), the efficiency of perovskite solar cells (PSC) increased from 14.1% in 2013 to 23.7% in just six years by 2019 [63]. Consequently, PSCs hold promising prospects for future development.

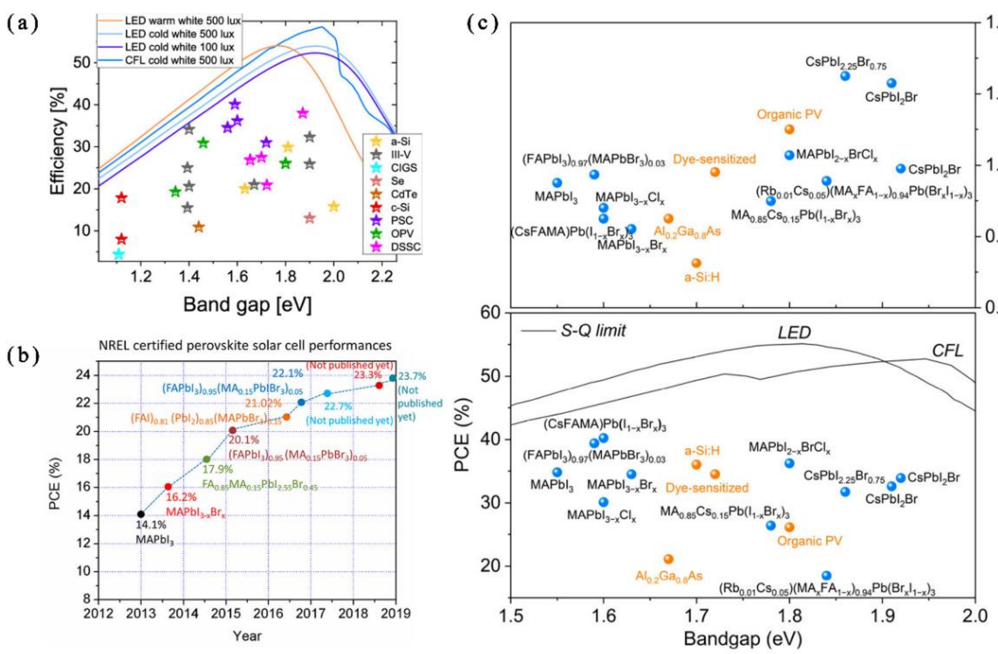

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Figure 5. (**a**) Functional relationship between performance and bandgap of several photovoltaic technologies when indoor light is between 50 and 3000 lx [64]; (**b**) Development of perovskite solar cells PCE [63]; (**c**) Comparison of PCE and V_{OC} between perovskite IPV and other IPVs [65].

4.2. Advantages

4.2.1. Excellent Photoelectric Property

Compared with traditional solar cells which can only absorb a fixed spectrum of light, perovskite can ensure that the maximum light sensitivity of the cell right pairs its light source spectrum, making it an ideal choice for self-powered and sustained operation in IoT sensors. Among various perovskite types, halide perovskites stand out due to their superior adjustable bandgap, bipolar charge transport characteristics [66], strong light absorption, long carrier lifetime, and solution processability. They not only exhibit outstanding performance in outdoor environments but also achieve a conversion efficiency of over 40% in indoor photovoltaics (IPV) [63,65].

As shown in Figure 5(a), the tunable bandgap of perovskite leads to exceptional photovoltaic conversion performance. In current laboratory research on PSCs, the highest photovoltaic conversion efficiency has reached 26.1%, approaching the maximum efficiency of silicon cells at 26.7% [67].

Furthermore, in low light intensity indoor environments, perovskite demonstrates lower carrier density and recombination probability along with higher charge extraction efficiency. Therefore, the built-in electric field can drive carriers to move faster and generate a high fill factor (FF), as shown in Figure 5(c). The open-circuit voltage and photovoltaic conversion efficiency of indoor photovoltaic PSCs are notably higher than those of other materials [64].

4.2.2. Low Cost and Simple Preparation Process

Compared to other mature and emerging photovoltaic technologies, the manufacturing process of PSCs is simple and economical. With high solubility at temperatures below 100°C, PSCs have lower energy consumption. Silicon-based solar cells often require high-temperature environments and special manufacturing processes (such as texturing, anti-reflection coatings [68]), while perovskite thin-film can be deposited through a variety of simple processes, such as spin coating, printing, vapor-assisted solution deposition, thermal vapor deposition, inkjet printing, slit-die coating, and spray coating [69,70].

4.2.3. Excellent Mechanical Properties

PSCs exhibit outstanding mechanical properties, including light weight, flexibility, and transparency. As a result, compared to silicon-based solar cells, PSCs have significant potential for applications in portable, bendable, and wearable devices. This is particularly true for ultra-thin devices such as wearable sensors in IoT and flexible electronic products [71].

4.3. Applications of PSCs in IoT field

The application of solar cells in the field of IoT primarily serves as a power supply module for various sensors and devices. Currently, the development of conventional full-spectrum photovoltaic technology is relatively mature and has demonstrated excellent performance under conditions of ample outdoor illumination. However, compared to outdoor applications, progress in indoor photovoltaic technology has been relatively slow. This is mainly due to the fact that indoor environmental light typically comes from sunlight through windows or artificial lighting equipment. The spectral characteristics of these light sources differ significantly from outdoor sunlight, resulting in low energy density and limited wavelength range. Therefore, effective methods for utilizing photovoltaic power as an indoor power supply are currently lacking.

Indoor Photovoltaic (IPV) technology is generally defined as the application of photovoltaics under low incident light intensity conditions. Commonly used indoor light sources such as white Light Emitting Diodes (LEDs) and fluorescent lamps, along with a minimal amount of ambient diffuse light within a spectral range of 400-750 nm and illuminance levels ranging from 200 to 1000 lux [72,73]. The power density is notably lower than that provided by natural light sources. Hence, the design considerations for indoor photovoltaics differ significantly from those applied to outdoor systems.

However, due to the mild indoor environmental conditions with no UV radiation, lower humidity, reduced thermal stress, and absence of other harmful gases, the issue of PSCs' low resistance to humidity or other gases is not prominent. Furthermore, its outstanding performance in indoor photovoltaics has positioned it as one of the ideal power supply methods for indoor IoT sensors [74]. Taking lead halide perovskite solar cells as an example, their adjustable band gap can perfectly match the spectral distribution of indoor light sources and effectively power indoor IoT devices [75]. Through optimization, lead halide perovskite solar cells can simultaneously collect direct, diffused, and reflected light to achieve higher photoelectric conversion efficiency [76], meeting the power requirements of various low-power electronic devices and sensors [77]. Additionally, compared to silicon-based solar cells, its manufacturing technique is relatively simple, which is crucial for large-scale deployment of sustainable energy in IoT systems [78].

In 2024, Ma et al. [79] reported a wide-bandgap PSCs to realize 44.72%-efficient indoor photovoltaics. The incorporation of a trace amount of dual additives enables a highquality and less defective wide-bandgap perovskite film with mitigated halide segregation, leading to the suppression of bulk trap-induced nonradiative recombination losses. The NiO_x-based inverted champion cell under one-sun illumination generates a record power conversion efficiency (PCE) of 21.97%, an impressive FF of 83.4%, a J_{sc} of 21.56 mA/cm^2 , and a V_{oc} of 1.25 V for 1.71-electon-volt wide-bandgap perovskites, as shown in Figure 6. Such devices also show high operational stability over 800 hours during T95 lifetime measurements. This study proves that wide-bandgap perovskite, such as metal halide perovskite, is a promising material to make indoor PSCs.

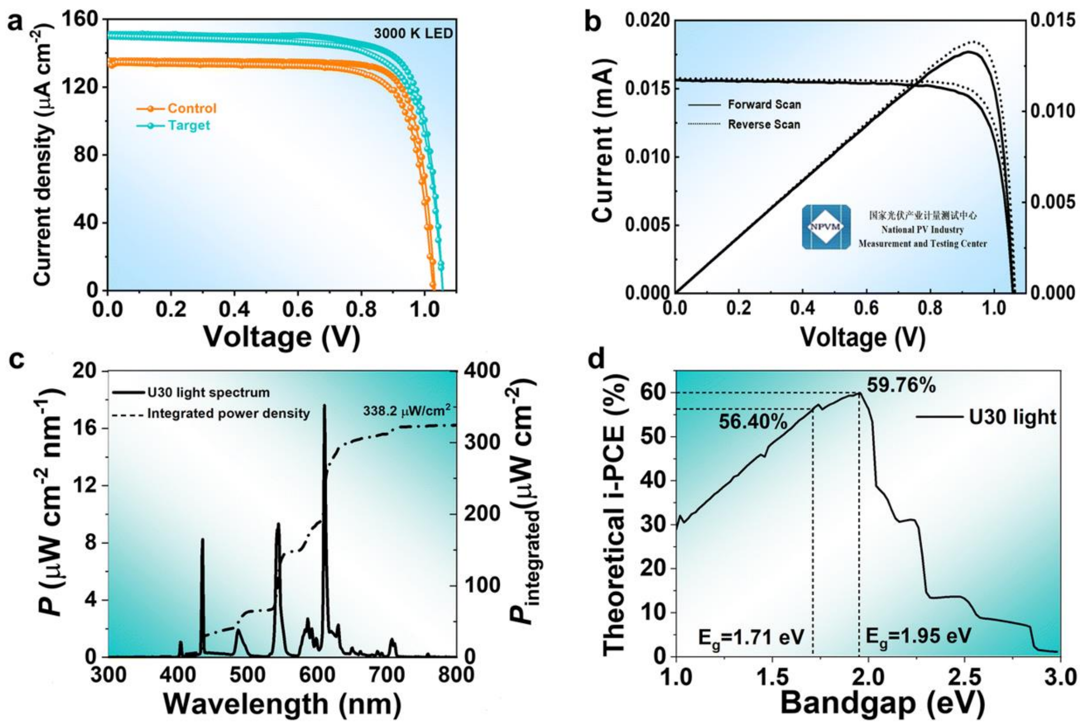

Figure 6. Indoor photovoltaic performance of wide-bandgap PSCs: (**a**) current density–voltage (J–V) curves of control and target wide-bandgap PSCs under LED light with 1000 lux and 300 K; (**b**) indoor current–voltage (I–V) and corresponding spectrum distribution with an integrated power density of 338.2 mW/cm^2 under U30 light of 1000 lux; (**c**) and (**d**) U30 light spectrum distribution with an integrated power density of 338.2 mW/cm^2 and the corresponding Shockley–Queisser limit of PCE of an ideal photovoltaic device as a function of bandgap energy [79].

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Furthermore, due to the excellent mechanical properties, PSCs can be made foldable and stretchable, making them applicable to various fields such as e-paper and electronic clothing. At the same time, various anti-impact, highly flexible special devices can also be achieved, such as the flexible perovskite-based electronic shelf label (PESL), portable electronic products, textile electronic integration, and transportation units [80,81].

As shown in Figure 7, in the future, IoT-enabled devices will also play a crucial role in the full life cycle monitoring scenarios such as smart homes and green factories [82]. Perovskite indoor photovoltaics can effectively solve the problem of sustained power supply for large IoT systems, providing green and sustainable clean energy for the system.

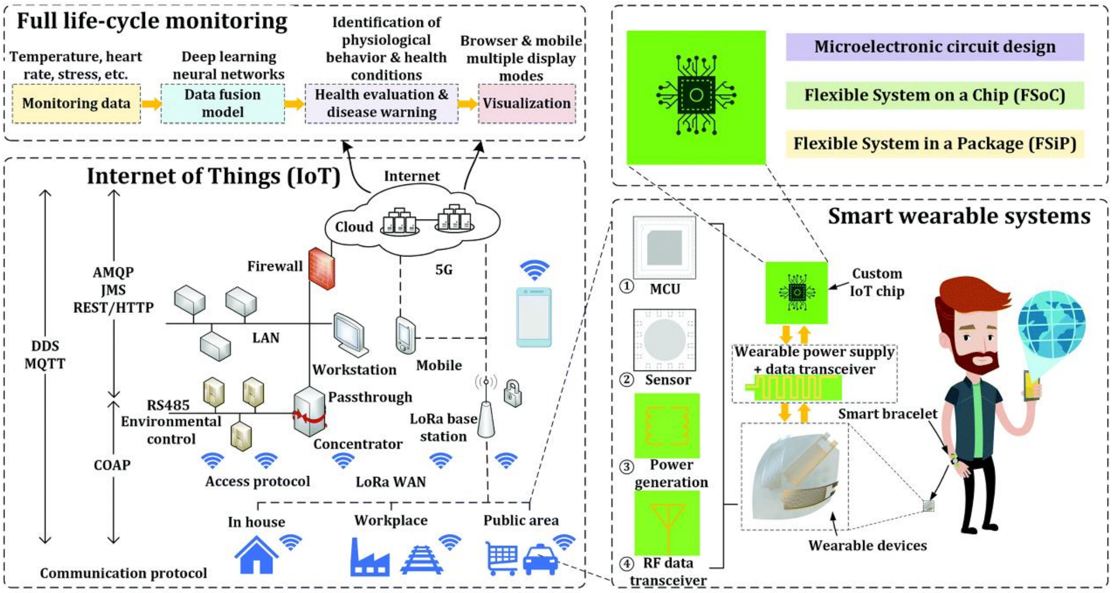

Figure 7. Standalone iot enabled systems for full lifecycle health monitoring, depending on the application scenario, the system can be powered by a green and sustainable power source [82].

5. Discussion

Perovskite, as a novel type of semiconductor material, has garnered extensive attention in the fields of sensors and indoor photovoltaics due to its outstanding photoelectric conversion properties, adjustable and easily processable energy level structure, as well as controllable crystal structure and morphology. This highlights its potential application in IoT domain. Furthermore, with the rapid advancement of 5G communication technology, there is an increasing demand from both enterprises and individuals for a greater number of sensors. However, traditional sensors are generally costly and unsuitable for the expansion of IoT technology. In contrast, perovskite sensors offer cost-effectiveness and exceptional detection performance, positioning them to excel in the realm of IoT.

Despite the promising prospects for perovskite sensors in IoT applications, it is essential to continue addressing technical and practical challenges that arise during their implementation.

First, the long-term stability of PSCs is relatively weak [83,84]. Studies have shown that perovskite materials are unstable when exposed to environmental factors such as oxygen, water, heat, and light. In addition, some studies have shown that the intrinsic properties of perovskite materials, such as ion migration and low defect formation energy, play an important role in promoting the rapid decomposition of perovskite thin films, leading to PSCs that cannot meet the market requirement of a 25-year lifespan. In this case, the following solutions can be taken: adjusting the proportion of perovskite components to increase the proportion of bromine and iodine; replacing the high-volatility A-site MA cation with FA or Cs completely or partially; using 2D material polymers and fullerene derivatives to passivate the defects in perovskite thin films; increasing the grain size to avoid the appearance of PbI_2 [85].

Second, the potential health risks caused by the leakage of toxic lead components. The lead leakage from the mixed halide perovskite into the environment may cause potential dangers. Therefore, the lead capture in the encapsulation layer, charge transport layer, and perovskite layer, as well as the overall device level packaging and end-of-life recycling, need to be considered [86–88].

Third, it is difficult to control the quality of perovskite thin films. Although the conversion efficiency under indoor lighting has been greatly improved in recent studies, there is still a large gap with the Shockley-Queisser theoretical efficiency. This is mainly because the perovskite thin films prepared by the widely used reverse solvent method cannot get high-quality perovskite thin films with micron thickness, resulting in serious light loss, low short-circuit current density, and serious non-radiative recombination loss, further reducing the open-circuit voltage and fill factor. Therefore, it is urgently needed to study new thin film preparation methods or reduce the defects generated during thin film preparation to increase the thickness of the film, regulate the film bandgap, and improve the film quality, thus further improving the indoor photovoltaic device performance.

Fourth, there is no uniform indoor spectral standard. To promote subsequent research and production, a uniform indoor spectral standard needs to be established, so that the performance indicators of indoor photovoltaics can be tested.

Funding: This work was supported by the National Natural Science Foundation of China (22379017, 22105018, and 52372135), and University-level Undergraduate Training Program for Innovation and Entrepreneurship (BIT2023LH063).

Conflicts of Interest: The authors declare no conflicts of interest.

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 doi:10.20944/preprints202408.1371.v1