Use of Perovskites for Optosensors

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Abstract. The work is devoted to the determination of the place of perovskites among the other materials for optosensors. The features and advantages of this material are determined. The methods for the manufacture of perovskites and the latest technical developments in their application are analyzed. Perovskite and silicon photosensors are compared. A comparative table of perovskite compounds is drawn up. It is determined that perovskites have great potential for their use in low-voltage, inexpensive, high-speed, highly sensitive and ultra-highly integrated optoelectronic devices.

Introduction

Perovskite-based optosensors have become more and more promising topic in the field of optosensors in recent years. Metal halide perovskites have heightened wide research interest due to their unique and near-ideal optoelectronic properties, including a direct band gap, high absorption coefficient, long electron-hole diffusion length, and high defect resistance. Over the past few years, a large number of works have been published concerning the improvement of optosensors, including the increase of their sensitivity and long-term stability, and the expansion of the spectral range of sensors.

Chemical Composition and Properties of Perovskites

Perovskite is a relatively rare mineral on the Earth's surface. It was first discovered in the Ural Mountains and was named after the Russian nobleman and mineralogist Lev Perovskiy (founder of the Russian Geographical Society). Perovskite is a source of titanium, niobium and a number of other elements. Perovskite crystals are of a cubic (pseudocubic) shape ABX_3, where A is a monovalent cation ($CH^{3+}NH^{3+}$(MA), Cs^{+}, etc.), B is a divalent metal cation (Pb^{2+}, Sn^{2+}, etc.), and X is a halide ion (Br^{-}, Cl^{-} и I^{-}) [1]. Atoms of monovalent cations in perovskite are located at the sites of a slightly distorted cubic lattice. Divalent metal cation atoms are located in the centers of the pseudocubes. Atoms of halide ions form almost regular octahedra around titanium atoms, which are slightly turned and tilted relative to ideal

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positions. The scheme of the lattice is shown in Figure 1 [1]. Often-observed crystals, sometimes quite large, are of a cubic shape.

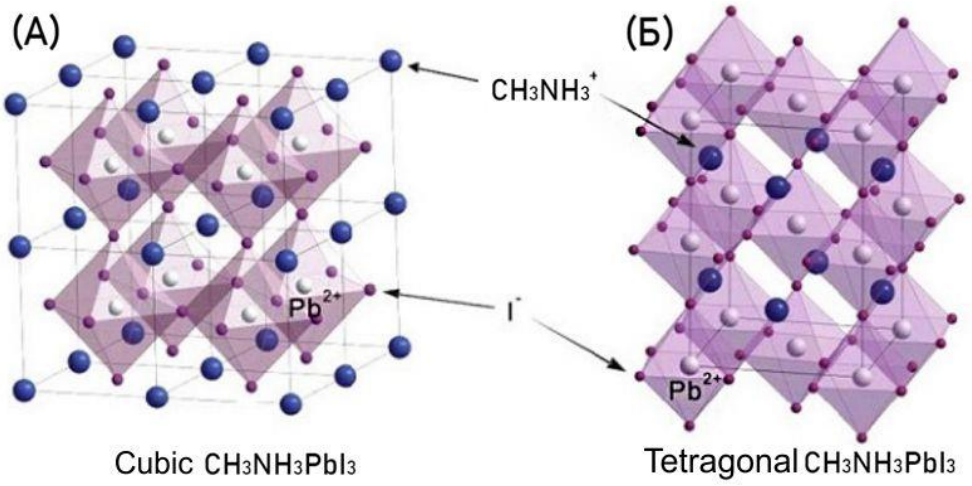

Fig. 1. Cubic (A) and tetragonal (B) lattices [1]

Perovskites can also have a tetragonal lattice. The type of the lattice plays an important role in what properties the perovskite will have. Thus, there is a strong correlation between the photocurrent and the photoluminescence decay time, which lies in the nature of the crystal structure. Therefore, the tetragonal phase shows a higher photoconversion efficiency compared to the cubic one. Depending on the impurities trapped or introduced into their lattice, perovskites can have a range of such interesting properties as superconductivity, spintronics, and catalytic properties. Perovskite compounds include oxides, halides, and intermetallic compounds. All the foregoing makes this material very interesting for researchers in many areas of electronics.

Use of Perovskites in Photodetectors and Their Classification

Perovskites are mainly used in solar cells, as well as in photodetectors. Photodetectors, which work by converting incident light into electrical signals, are the basis of various industrial and scientific applications such as imaging and object detection systems, optical communication, and environmental observation [2].

Optosensors, or perovskite-based photosensors, can be divided into two categories: photoelectric and photoconductive photosensors. According to the spatial arrangement of the photoactive medium and electrodes, perovskite-based photosensors can be further divided into vertical and horizontal ones. As a rule, vertical photosensors provide fast response and low drive voltage. In their turn, horizontal photosensors demonstrate a slow response and a high control voltage due to the large distance among the electrodes [3].

In recent years, metal halide perovskites have attracted wide research interest due to their unique and near-perfect optoelectronic properties, including a direct band gap (1.6 eV), large absorption coefficient, long electron-hole diffusion length, detectivity, high mobility and lifetime of charge carriers, as well as high defect resistance. Nanostructured perovskite photosensors have more advantages in ultra-high sensitivity and ultra-fast response speed. The main parameters of photo sensors are given in Table 1.

Among various perovskite compositions, such substances as $CsPbX_3$ and $CH_3NH_3PbX_3$ ($MAPbX_3$) (X = Br, I) attracted more attention in photodetection. Thus, atomically thin 2D $CsPbBr_3$ nanolayers have recently been obtained, which are characterized by high performance in a flexible photosensor with solution processing [4]. The UV–vis absorption spectrum of the $CsPbBr_3$ nanolayers showed a favorable absorption capacity and a direct band gap of about 2.32 eV. A flexible photosensor made of a CsPbBr3 nanosheet demonstrated good dynamic characteristics when switching light, as well as high sensitivity. These results showed that the $CsPbBr_3$ nanosheet has a great potential when used in highly sensitive sensors [4].

Table 1. Parameters of Photosensors

Parameter	Description
Photoresponse	The ratio of the photocurrent to the power incident on the active region. R = (Ip − Id) / (PA), where Ip – photocurrent, Id – dark current, P – intensity of light, A – active area
Photoelectric conversion efficiency (EQE)	EQE = Rhc/e, where h – action constant, c – speed of light in vacuum, e – elementary charge
Gain (G)	The number of charge carriers through the external circuit for one incident photon: G = tl/tt = tl(μV)/d2, where tl – life span of carrier, tt – transmission time of carrier, μ - mobility of carrier, V – bias voltage, d – channel length
Specific detectivity (D)	$D* = \frac{S\sqrt{\Delta f}}{\Phi_{\text{П}}}$, where S – active area of photosensor, Δf - RMS-noise, used to evaluate the ability of a 1 cm^2 receiver to detect a single 1 W flux in a 1 Hz bandwidth.
Linear dynamic range (LDR)	Linear dynamic range - the range in which the current response of the photosensor is linearly proportional to the light intensity. LDR = 20 log (Ip*/Id), where Id – dark current, Ip – photocurrent.
Ratio of time constants	The ability of a device to track random light signals

Thus, $MAPbI_3$ metal-semiconductor-metal (MSM) film photosensors showed a wide photocoupler range from 310 nm to 780 nm with the photoresponse of 3.49 A/W and external quantum efficiency (EQE) of 1.19×10^3% [5]. However, there is an inherent paradox of perovskites, which consists in the need to simultaneously possess both low dark currents and high photocurrents. The former requires a large number of defects or barriers that appear in the polycrystalline film to prevent the transfer of thermally excited carriers [6], while the latter requires single crystals with good crystallinity for efficient charge transfer. Compared with polycrystalline film photosensors and bulk crystals, nanostructured photosensors show superior performance. A large surface-to-volume ratio of nanostructures leads to an increase in the service life of the photocarrier, which contributes to an increase in sensitivity. In addition, the reduced size reduces the carrier transmission time and improves the response speed [7]. Therefore, the performance of a photo sensor based on nanostructured perovskites will be higher.

Thus, high sensitivity of 1294 W^{-1} with ultrahigh detectivity 2.6×10^{14} Jones was obtained in a photosensor based on α-$CsPbI_3$ nanowire. What is more, ultrahigh response rate

(19/25 μs) was obtained in a photosensor based on atomically thin 2D $CsPbBr_3$ nanolayers [8]. Ultra-high gain of 10^7% was demonstrated by a phototransistor based on $CsPbI_3$-xBrx quantum dots (QDs)/ MoS_2 monolayer heterostructure [9].

High-quality $MAPbI_3$ with the morphology of nanowires (NW) and nanoplates has been successfully obtained by a simple solution immersion method [10].

Schematic diagrams of photosensors based on nanowires and nanoplates are shown in Figures 2 A, B [10, 25]. Both the photocurrent and the switching ratio were well maintained, the switching ratio was controlled by adjusting the applied light intensity. The on/off ratio of the $MAPbI_3$ photosensor based on nanowire reached 314, and the on/off ratio of the nanowire based photosensor reached 1,210, which is several orders of magnitude higher than that of the photosensor based on polycrystalline film [11]. Nanoplate based devices generally show relatively better performance than nanowire based devices due to higher quality crystals with smoother surface and more regular shapes. This suggests that higher performance can be expected by further improving the quality of the crystals. Due to the low sensitivity caused by the poor charge transfer of perovskites, many studies combined perovskites with high mobility materials to increase sensitivity.

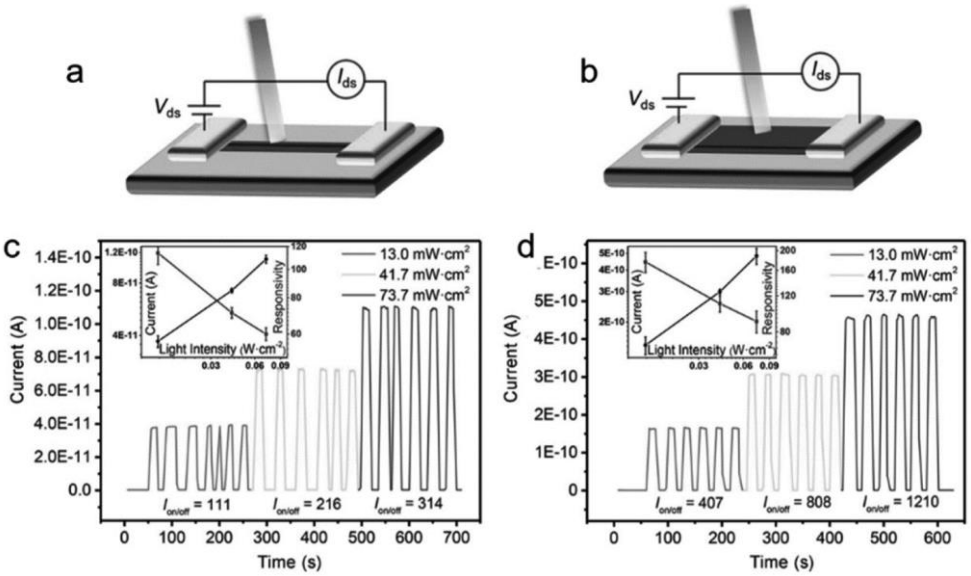

Fig. 2. Structure of photodetectors based on $MAPbI_3$ nanowires (A) and nanoplates (B) [25]

Experiments have shown that the photosensor based on the $CsPbBr_3$ composite nanosheet/carbon nanotubes (CNT) (6%) exhibits the best response [12]. The highest external quantum efficiency (EQE) reaches 7,488%, and the highest sensitivity reaches 31.1 A/W [12]. The on/off ratio reaches 823 [12]. The nonlinear input–output curve demonstrates the Schottky contact between the $CsPbBr_3$/CNT nanosheet and electrodes [12]. The rise and fall times were 16 μs and 0.38 ms, respectively [12]. The high response and speed indicate fast separation and efficient recovery of photogenerated carriers, which can be explained by the improved electrical conductivity of CNTs.

Photodetectors Based on 1D Perovskites

Not so long ago, a photosensor based on single-crystal arrays of $MAPbI_3$ microwires (MW) was developed [13]. The device showed obvious response to visible light, but it was rather insensitive to ultraviolet and infrared radiation. High sensitivity of 13.57 A/W, high

detectivity of 5.25×10^{12} mm, and wide LDR have been achieved in MW photo sensors [14]. Compared to thin-film photosensors, MW-array photosensors show better stability when recording dark and photocurrents of photosensors. The outstanding performance of the device can be attributed to the high optical absorption coefficient of $MAPbI_3$ and the MW high crystallinity.

Liu et al. [8] synthesized $MAPbI_3$ MW highly crystalline arrays via the solvent recrystallization method. The work shows the energy band diagram. The photoresponse makes 0.04 A/W, while the on/off ratio makes 0.84×10^4, with the detectivity of 0.6×10^{12} Jones and the rise and fall times of 178/173 μs. The results show that $MAPbI_3$ MW show good prospects for high performance photosensors.

By interacting with a Pb-containing nanowire (NW) precursor with mABR and HBr in an organic solvent, porous $MAPbBr_3$ NWs were successfully obtained [8]. The UV/Visible absorption spectrum indicates favorable absorption capability with a straight band gap of about 2.22 eV. On/off ratio of 61.9 indicated a good response to light intensity. As shown, the rise and fall times made 0.12 s and 0.086 s, respectively. The excellent photovoltaic properties are mainly due to their unique 1D porous geometry, numerous active sites and sufficient light absorption.

Zhou et al. [9] successfully obtained porous $MAPbBr_3$ NW. The UV/Visible absorption spectrum indicates a favorable absorption capacity with a direct band gap of about 2.22 eV. Good ohmic contact was demonstrated by a typical linear and symmetrical I/O curve. The rise and fall times made 0.12 s and 0.086 s, respectively. The excellent photovoltaic properties are mainly due to their unique 1D porous geometry, numerous active sites and excellent light absorption.

Deng et al. [13-18] reported a high-quality single-crystal $mapB(I1\text{-}xBrx)_3$ (x = 0, 0.1, 0.2, 0.3, 0.4) NW with an absorption spectrum in the range from 680 to 780 nm by modifying the I/Br ratio. A schematic diagram of the device based on NP. NW-based photosensors demonstrated an ultra-high sensitivity of 1.25×10^4 A/W due to the high-quality NW crystal structure. In addition, the device also obtained other quality indicators such as 3dB bandwidth (0.8 MHz), high detectivity (1.73×10^{11} dB), LDR 150 dB. Such high performance can be explained by the long service life of carriers and high carrier mobility in highly crystalline $MAPbI_3$ NWs. Thus, many high-performance integrated optoelectronic devices could be produced using NW-arrays.

The work [19] shows successfully synthesized $CsPb(Br/I)_3$ nanotubes using simple hot injection method. The PL and UV-vis absorption spectra indicate that the band gap makes ≈ 1.98 eV. The light sensitivity of the photosensor reaches 10^3 ISO, and the rise and fall times make 0.68 s and 0.66 s, respectively. The photosensor is well matched to ohmic characteristics with a linear I/O curve. The I/O curve showed a surprisingly high on/off ratio of 2,000. The good performance of the photosensor can be attributed to the long lifetime and short transit time of photocarriers in $CsPb(Br/I)_3$ nanorods with high surface to volume ratio and high density of trap states at a deep level.

Gao et al. [20] successfully synthesized a $MAPbI_3$ nanowire array by optimizing one-step self-assembly. It turned out that devices prepared on the basis of OA (oleic acid)-passivated $MAPbI_3$ nanowires had the best performance. The structure of the photosensor is schematically shown in Figure 3 [20].

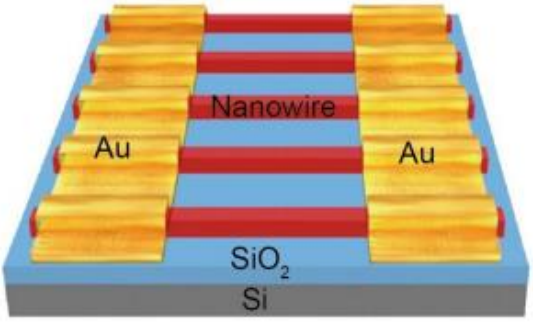

Fig. 3. Structure of a photosensor based on OA (oleic acid) passivated $MAPbI_3$ nanowires [20]

Broadband photoresponse ranges from 400 nm to 750 nm, design sensitivity is 0.45 A/W, rise and fall time makes within 0.1 ms, on/off ratio is 4,000, which reflects the excellent light sensitivity of the device. In addition, ultra-low dark currents result in low carrier density and low thermal radiation (recombination) rates and allow the device to detect very weak optical signals. What is more, a detectivity of 2×10^{13} Jones was achieved. The improved performance can be attributed to increased carrier life owing to OA passivation, which can reduce the number of non-emitting composite centers on the surface of the nanowires and give the device more time to collect and transfer photogenerated carriers.

Scientists from China have synthesized lattices of α-$CsPbI_3$ perovskite nanowires with predominant (100) crystallographic orientation to further improve the performance of the photosensor [20]. The high intensity of photoluminescence (PL) and the long lifetime of PL have demonstrated low trap density in α-$CsPbI_3$ nanowires, which is stipulated by their suppressed grain boundaries and surface defects. High-performance photosensors based on ready-made nanowires were designed. The photosensor has high sensitivity of 1,294 1/W and detecting power of 2.6×10^{14} Jones. The rise time makes 0.85 ms and the fall time is 0.78 ms. Performance can be maintained at 90% after 30 days, showing excellent long-term stability. High performance is mainly achieved through fewer grain boundaries and ordered crystallographic orientation.

To reduce lead toxicity for future applications, the scientists fabricated lead-free, all-inorganic $CsSnX_3$ (X = Cl, Br, I) perovskite nanowire-arrays on a mica substrate with [100] growth direction by chemical vapor deposition. In addition, the narrow band gap of the $CsSnI_3$ nanowire array expands the possibilities of optoelectronic applications of perovskites from the visible to the near infrared region, and the $CsSnI_3$ nanowire array photosensor is the first registered near infrared detector. The maximum sensitivity was observed at a wavelength of 940 nm, so the photosensor is irradiated with a laser with a wavelength of 940 nm. The photocurrents increase with the incident radiation increasing intensity. The rise and fall times made 83.8 and 243.4 ms, respectively. The fast photoresponse can be explained by the high quality of the $CsSnI_3$ nanowire array with fewer surface states and trapping centers. Sensitivity and detectivity made 54 mA/W and 3.85×10^5 Jones, respectively. A polarization-sensitive UV photodetector was constructed based on another completely inorganic perovskite $CsCu_2I_3$ nanowire. The PL intensity anisotropy coefficient can reach 3.16. The $CsCu_2I_3$ device can respond to light from 230 to 350 nm. The performance of $CsCu_2I_3$ nanowire photosensor shows high performance, such as high on/off ratio of 2.6×10^3, ~32.3 A/W photoresponse, high detectivity of 1.89×10^{12} Jones, and fast response speed of 6.94/214 μs . In addition, good flexibility and stability have been demonstrated by 1,000 bending cycles without any photoresponse degradation.

Photosensor Based on Other Nanostructured Perovskites

Paper [21] describes the results of the manufacture of a photosensor based on completely inorganic nanocrystals (NC) of $CsPbBr_3$ perovskite with a synergistic effect of preferential orientation and a plasmon effect. The schematic diagram of the device is shown in Figure 4 [21]. The peak sensitivity value makes 20.92 mA/W. An increase below 520 nm is explained by an increase in the concentration of electron-hole pairs. The light on/off ratio makes >1.6 × 10^5.

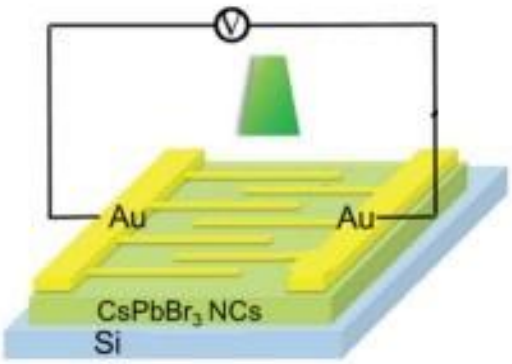

Fig. 4. Schematic diagram of a photosensor device based on completely inorganic $CsPbBr_3$ perovskite nanocrystals [21]

Table 2. Types of Perovskites and Their Key Parameters

Dimension	Perovskite	R[A/W]	D (Jones)	EQE [%]	On/off ratio	LDR	Rise/fall time
2D	$CsPbBr_3$	0.25	-	53%	-	-	19 μs/25 μs
	$MAPbI_3$	-	-	-	1210	-	-
	$CsPbBr_3$/CNTs	31.1	-	7,488%	-	-	16 μs/0.38 ms
1D	$MAPbI_3$	13.57	5.25×10^{12}	-	-	-	-
	$MAPbI_3$	0.04	0.6×10^{12}	-	0.84×10^4	-	178 μs/173 μs
	$MAPbBr_3$	-	-	-	61.9	-	0.12 s/0.086 s
	$MAPb(I1-xBrx)_3$	1.25×10^4	1.73×10^{11}	-	-	150	-
	$MAPb(I/Br)_3$	10^3	-	-	2,000	-	0.68 s/0.66 s

	$MAPbI_3$	0.45	2×10^{13}	-	4,000	-	<0.1 ms
	$MAPbI_3$	1.2	2.39×10^{12}	-	160	-	-
	$CsPbI_3$	1294	2.6×10^{14}	-	-	-	0.85 ms/0.78 ms
	$CsSnI_3$	0.054	3.85×10^{5}	-	-	-	83.8 ms/243.4 ms
	$CsCu_2I_3$	32.3	1.89×10^{12}	-	2.6×10^{3}	-	6.94 μs/214 μs
Others	$CsPbBr_3$	0.0209	-	-	1.6×10^{5}	-	0.2 ms/1.3 s
	$CsPbX_3$	-	-	-	10^{5}	-	24 ms/29 ms
	GQDs/$CsPbBr_3$	0.24	2.5×10^{12}	57%	7.2×10^{4}	-	1.16 ms

In [22], red emitting $CsPbI_3$ NCs were chosen for the manufacture of photoelectronic devices due to the relatively longer lifetime of radiation than green and blue emitting CsPbX3 NCs (X = Cl, Br). The finished photosensor features high performance, including high light sensitivity of 10^5 ISO, reproducible response to on/off cycles, fast response time of 24/29 ms, which shows promising applications in photovoltaic devices.

In [23], nitrogen-doped graphene quantum dots (GQD)/$CsPbBr_3$ NC photosensors were constructed, in which GQDs act as an electron transport layer, and $CsPbBr_3$ act as a light absorber. The lifetime of PL NC $CsPbBr_3$ passivated by GQD decreases equally, demonstrating significant charge transfer at the GQD/$CsPbBr_3$ interface. Heterostructure based photosensor has higher performance than pure one, such as higher on/off ratio of 7.2×10^4, higher photoresponse of 0.24 A/W, large detectivity of 2.5×10^{12} Jones, 57% gain, faster fall time of 1.16 ms.

In [24], the results of creating photo sensors based on ITO thin films are presented. Table 2 shows the systematization of perovskite parameters.

Methods of Perovskite Production

Perovskites can be produced with the use of a variety of dissolution and vapor deposition techniques. The approaches described for the synthesis of perovskite active layers are as follows:

- precipitation from the precursor solution in one stage;
- sequential deposition in two stages;
- deposition from two sources from the vapor phase;
- deposition from the vapor phase auxiliary dissolution process;
- sequential vapor deposition.

In general, we can classify perovskite synthesis methods into the following broad sections: dissolution methods (treatment of solutions); treatment of solutions using the vapor phase and vacuum deposition.

Other processing methods, such as spray coating, inkjet printing, and electrospinning, can also hold great promise in the manufacture of perovskites. In terms of the design of perovskite

photo sensors, the main problems are different for their three types (photodiodes, photosensor, and phototransistors). For perovskite photodiodes, the introduction of an intermediate layer to control the energy range and passivate traps at the interface has become a universal strategy for improving performance, which made it possible to suppress dark current and increase photocurrent. For perovskite photosensors, the device gain increase is critical. Low dimensional perovskites are advantageous due to their small size, which means less channel length.

Despite the impressive advances made with the various device development strategies discussed above, there are still some shortcomings that limit the development of perovskite materials. These photosensors typically operate at a high bias voltage, which results in high dark current and limits the detectivity of the devices. Dark current can be suppressed by interlayer or interfacial modification. In addition, the self-contained perovskite also facilitates the use of photosensors at low drive voltages or in low light conditions. Due to the wide band gap of Pb-based perovskites, most perovskite photosensors typically have poor near infrared (NIR) sensitivity. By replacing Pb with Sn or by alloying materials with Sn, absorption in the NIR range can be increased.

In particular, low-cost solution-treated perovskite photodetectors exhibit high sensitivity and a wide detection range. It is noteworthy that even a thin perovskite layer (several hundred nanometers) is sufficient to achieve light absorption in the ultraviolet-visible range. As is known, the energy of photons depends on the frequency of the wave. Hence, perovskite-based solar cells can absorb high-energy photons, which leads to the formation of hot carriers, such as electrons. The lifetime of hot electrons in silicon photosensors makes about 1 picosecond, after which the electron releases energy in the form of heat. In perovskite photocells, the lifetime of hot electrons is much longer and makes about 100 picoseconds. In addition, during this time, the electrons have time to overcome about several hundred nanometers, which is comparable to the thickness of a semiconductor. These parameters of perovskite sensors can significantly increase the efficiency due to the capture of hot electrons.

When it is reduced to nanometer scales, the material will exhibit different properties compared to its dimensional counterparts. Size-dependent optical band gaps, large extinction coefficient, high photoluminescence quantum yield, and quantum dot multiple exciton generation characteristics make perovskite the most suitable material for optoelectronic devices.

There are 2 methods for the formation of perovskite quantum dots/nanocrystals: ligand-assisted re-precipitation (LARP) and hot injection. An example would be the synthesis of colloidal perovskite quantum dots in the solution phase, in which 6 nm $MAPbBr_3$ quantum dots were obtained by re-precipitation using organic ammonium cations with an alkyl chain of medium length as in ligands. Synthesized $MAPbBr_{3-x}Cl_x$ and $MAPbBr_{3-x}I_x$ nanocrystals showed a full range of band gaps varying over a wide range (1.6eV-3eV).

Inorganic $CsPbX_3$ nanocrystals are obtained by hot injection. $CsPbCl_3$ and $CsPbI_3$ were obtained by halide exchange reactions using lithium salts (LiX, X = Cl, Br and I). Photosensors made of $CsPbI_3$ showed a high on/off photocurrent, while highly sensitive hybrid photosensors based on graphene-$CsPbBr_{3-x}I_x$ perovskite nanocrystals have high photosensitivity and detectivity.

Based on early research work, perovskite quantum dots were widely used as LEDs. However, a growing number of research papers suggest the efficient use of perovskite quantum dots as photosensors.

Prospects for the Use of Perovskites

As mentioned earlier, compared to silicon sensors, perovskite sensors have an order-of-magnitude longer lifetime of hot electrons, which is an advantage over silicon sensors.

Even the efficiency of perovskite single-layer photovoltaic cells reaches up to 25 percent, which corresponds to the best serial silicon solar cells.

Also, small changes in the composition of perovskite layers in sensors of various kinds make it possible to adjust the band gap, as a result of which electrons respond to different frequencies of light waves. The 500nm thick perovskite film contains enough layers to generate electricity at all frequencies in the visible light range.

Perovskite cells can be fabricated using simpler solution chemistry techniques in traditional laboratory conditions, unlike silicon solar cells, which require costly multi-step processes with extreme temperature and vacuum control systems. As mentioned, $CH_3NH_3PbX_3$ is the most popular perovskite-like material. Upon contact of such a compound with water and oxygen, degradation and destruction of the structure can occur, which is a disadvantage for perovskite photosensors.

Along with the degradation, the disadvantage of perovskites is their instability. For example, in solar perovskite cells, at best, 10% of power is lost in a few months of operation, which is a lot compared to silicon cells, in which 0.5% of power is lost after a year of operation.

In addition, the disadvantage of perovskites is the lack of environmental friendliness. The lead in the structure of perovskites complicates the disposal of sensors and increases the risk of environmental pollution.

The toxicity of Pb-based perovskites is still difficult to overcome because Pb is required to achieve high performance in perovskite optoelectronics. Although great efforts have been made in the field of Pb-free perovskite photovoltaics, there is still a long way to go in order to apply lead-free perovskites in photosensors and improve the photoelectric conversion efficiency of lead-free perovskite optoelectronics.

First of all, additional research efforts should be focused to fully understand the properties and eliminate the aforementioned bottlenecks in order to improve the performance of future devices.

Conclusion

This paper presents an analysis of advances in research on photo sensors based on nanostructured perovskites. It is shown that the characteristics of the detectors are affected by the type of device, as well as the structures of nanostructured perovskites with different morphologies.

In general, nanostructured perovskite photosensors perform well due to long carrier life, high carrier mobility, and low carrier recombination, which results from a small number of grain boundaries and lower trap state density. The conclusion is that nanostructured perovskites have great potential for applications in low-voltage, low-cost, high-speed, high-sensitivity, and ultra-highly integrated optoelectronic devices.

Despite the significant progress made in the field of perovskite photosensors, there are still many problems. First, both photosensors and phototransistors improve only part of their parameters. However, an ideal photosensor should improve performance, including high sensitivity, greater detectivity, high speed, etc. Secondly, perovskites easily decompose in air in the presence of oxygen and moisture. Thus, the instability of perovskite hinders the commercial use of the device. The improvement of perovskite with new heterojunction protection strategies is of great importance as such designs have relatively greater stability. In addition, some sources reported only the best performance of the device, but ignored its

average performance, which would lead to a misleading influence concerning the industrialization, and also would show that the authors were not sure about the stability of the device. Finally, the toxicity of perovskite has cast a shadow over its use due to the use of lead in widely studied materials such as $MAPbI_3$ and $CsPbBr_3$. Therefore, more efforts should be made to obtain environmentally friendly perovskite materials with non-toxic elements instead of Pb.

The outstanding physical and chemical properties make perovskites ideal building blocks in the production of various types of optoelectronic devices. Different morphologies of materials can be selected for different devices. The best choice is usually polycrystalline film. The selection of a high-efficiency perovskite solar cell is a priority due to the large optical absorption coefficient over wide wavelength range, ultra-fast charge generation, high and microsecond balanced mobility, and slow recombination in perovskite materials. For LEDs, nanocrystals, quantum dots, or even 2D perovskites provide much higher light output. Nevertheless, single crystals and nanowires are more suitable for lasers because they require higher crystal quality.

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