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High-gain broadband organolead trihalide perovskite photodetector based on a bipolar heterojunction phototransistor

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ABSTRACT

Both a favorable material and designed structure are essential for a high-performance photodetector. For the excellent physical properties of organolead trihalide perovskites, with $CH_3NH_3PbI_3$ films serving as a base layer, a bipolar heterojunction phototransistor-type perovskite photodetector is proposed. Benefiting from this bipolar heterojunction structure, which is characterized by high gain and low work voltage, an optimized device exhibits high performance with a photoresponsivity of 125 AW^{-1} and an external efficiency of 3.62×10^4% at 427 nm with a low work voltage of 0.7 V. Additionally, such phototransistors have a broad photoresponsivity from 360 to 820 nm. These results demonstrate that the bipolar heterojunction phototransistor, which is widely used in inorganic materials, is a promising structure for organolead trihalide perovskite optoelectronic devices, paving a new way for developing high-performance photodetectors.

1. Introduction

Photodetectors, which can convert light into electrical signals, have become one of the most essential components in various applications, including image sensing, optical communication, industrial automation, and the Internet of Things (IoT) [1–3]. They have played an increasingly significant role in both industrial manufacturing and daily life. In order to get a well-performing photodetector, both a favorable material and designed structure are needed. Traditionally, the semiconductor materials that have been applied in commercial photodetectors are high-mobility crystallized inorganic materials, such as Si, InGaAs, GaN, etc. [4–8] Researchers continually look for novel photosensitive semiconductors that have comparable properties to commercial ones, but are less expensive, facilitate processing, and even mechanically flexible. Recently, organolead trihalide perovskites have been intensively studied as a promising photosensitive semiconductor material for high-performance, low-cost photovoltaic applications [9–12]. Organolead trihalide perovskites have many advantages, such as a suitable direct bandgap with a large absorption coefficient, long charge-carrier lifetime, and high mobility, which lead to a long-diffusion-length, low-cost solution based processing, etc. [13,14].

So far, the huge potential application of organolead trihalide perovskites as photodetectors has been successfully demonstrated in various architectures [15–19]. Currently, the *p-i-n*–type perovskite photodetectors with low operating voltage and simple architecture used as photovoltaic devices usually suffer from low photoresponsivity; while the MOSFET-type perovskite photodetectors with high photoresponsivity usually have a complex device architecture and work at high operation voltage [16,20]. A novel, simple-structure photodetector designed by Dong et al., with better performance than *p-i-n*–type and MOSFET-type perovskite photodetectors, has shown both high photoresponsivity and low voltage [17]. Although these photodetectors have been successful, none have had a saturation under voltage, which can give the device better noise tolerance to the voltage variations in real applications. Therefore, an alternate perovskite photodetector with all of these advantages is still highly demanded.

Bipolar heterojunction phototransistor architecture has proven itself a great structure for photodetectors historically, and are widely used in optical fiber communications, range-finder system, etc. [21,22] The first bipolar heterojunction phototransistor was introduced by Alferov et al. in the early 1970s [23]. A photodetector with a simple *p-n-p* or *n-p-n* heterojunction architecture can not only convert optical signals, but can also magnify the generated photocurrent, thus improving the photoresponsivity and signal-to-noise ratio [20]. In addition, its driving voltage is just slightly lower than the p-n–junction threshold voltage, which leads to a relatively low operational voltage. Moreover, the

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simplicity of two-terminal architecture enables the integration of a heterojunction phototransistor and other optoelectronic devices, which evolves into a new device with novel functions. Historically, bipolar heterojunction phototransistor-type photodetectors have been highly successful in Si/SiC and AlGaAs/GaAs [8,24,25]. Later, to lower the cost and introduce flexibility, an all-organic bipolar heterojunction phototransistor was constructed by Zukawa [26]. However, this phototransistor exhibited a low external quantum efficiency (EQE) of approximately 2.9%, due to the short carrier diffusion length of organic semiconductors, which places the problem back on the materials.

In this work, with a $CH_3NH_3PbI_3$ film serving as a base layer, benefiting from the long carrier diffusion length (up to 1 μm), broadband absorption, and low-cost solution process, a high-performance and low-cost perovskite-bipolar-heterojunction-phototransistor– (PBHPT-) type photodetector is realized. The photoresponsivity of the device reaches 125 A/W, with an EQE of 3.62×10^4% (over 10000 times larger than the organic one) at an incident light wavelength of 427 nm and a working voltage as low as 0.7 V. Additionally, the photodetector has a broad response from 360 to 820 nm. The results indicate that the PBHPT-type photodetector offers enough benefits to warrant further exploration and experimentation.

2. Results and discussion

2.1. Perovskite bipolar heterojunction phototransistor

A schematic of the device structure of a PBHPT is illustrated in Fig. 1(a). In the phototransistor, indium tin oxide (ITO) is adopted as the anode at the bottom. Above it, the first CuPc (*p*-type semiconductor) layer is evaporated as the emitter. Since CuPc is insoluble in N,N–dimethylformamide (DMF) solution, the one-step solution processed $CH_3NH_3PbI_3$ layer (*n*-type semiconductor, by self-doping [27]) is then successfully deposited on CuPc as the base, followed by another evaporated layer of CuPc as the collector. In the end, the entire PBHPT is finished by growing a top silver contact as the cathode. Different perovskite precursors and different perovskite base layer thicknesses are studied to optimize the performance.

2.2. Performance of PBHPT

When the device is under illumination, as shown in Fig. 1(a), the light passes through the emitter and reaches the perovskite base and the CuPc collector; the photocurrent I_{bc} is then generated by the base-collector junction. It is worth noting that the emitter-base-junction photocurrent is not taken into account, as it generates a reverse current. The photovoltage generated at the base-collector junction is in the opposite direction of the applied voltage, and will lower or even reverse the bias at the base-collector junction. The one generated at the emitter-base junction, however, is in the same direction of the applied voltage, and will always enhance the bias at the emitter-base junction. Since the emitter-base junction is under a forward bias, a small voltage enhancement will lead to a large increase of the emitter-base junction hole current I_E. Thus, the majority carriers in our device are the holes injected from the anode. When the device reaches a balance, most of the holes will directly flow through the base as the base is thin enough, and only a small part of them will recombine with the electron part of the photogenerated current I_{bc}. The proportion of totally emitted holes to recombined holes is equal to the proportion of I_E to I_{bc}, defined as β hereafter. The equivalent circuit is shown in Fig. 1(b). A PBHPT can be regarded as a photodiode paralleled with a bipolar transistor, which works in the amplified region and magnifies the photocurrent generated by the base-collector junction (I_{bc}). The output current of the PBHPT under illumination (or the light current I_l, $I_l = I_E + I_d$) can be usually described as

$$I_l - I_d = \beta \times I_{bc} = \mathrm{EQE} \times N_b \times e, \quad (1)$$

where I_d is the dark current of the PBHPT at the same bias as I_l, β the magnification rate (or the gain), EQE the external quantum efficiency, and N_b the number of incident photons per second. For an ideal phototransistor, $\beta \sim L^2/W^2$, where L is the diffusion length and W is the width of the neutral zone in the base, which is the base thickness minus the depletion length of *p-n* junctions (usually $L > W$), and e is the electronic change. For a standard triode, β can be derived by $(I_l - I_d)/I_{bc}$. However, there is no base electrode in a PBHPT, which makes the direct measurement of I_{bc} impossible. Therefore, the short-circuit current I_{sc} of a perovskite solar cell with the same preparation conditions is taken as an approximation of I_{bc}. The base-collector junction may be regarded as an electron-transport-layer free solar cell that makes its photocurrent I_{bc} smaller than a standard solar cell photocurrent I_{sc} [28]. Owing to this, the magnification rate β can be calculated without overestimating. More practically, the photoresponsivity R is used to describe the performance of the phototransistor, where I_{bc} is replaced by light intensity (L_{in}) and R is defined as $(I_l - I_d)/L_{in}$.

I-V measurements of PBHPT A (Fig. 2(a)) were carried out to reveal the electrical properties of the device. The dark current of PBHPT A, represented by the black curve, is relatively low and increases almost linearly with increasing bias in the range 0.1–0.7 V. Under illumination, the light currents (I_l) monotonically rise with light intensity. For the light currents measured under different power intensities, the shapes of

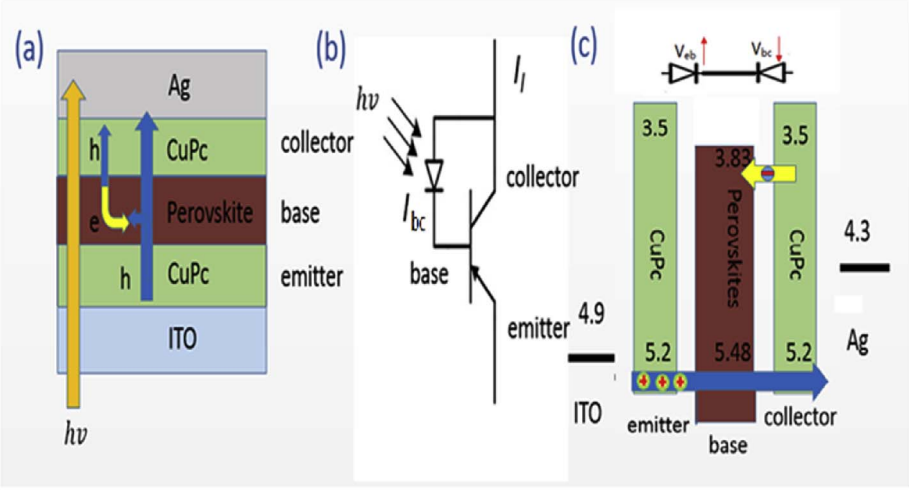

Fig. 1. Perovskite-bipolar-heterojunction phototransistor (a) structure, (b) simplified equivalent circuit diagram, and (c) energy bandgap of device.