Emerging intelligent devices that can simulate an artificial intelligence vision system are of great interest for the development of modern information technology. Nociceptor is a crucial sensory neuron that recognizes harmful inputs and sends pain signals to the central nervous system to avoid injury; however, visual nociceptors, considered to be a key bionic function to protect eyesight based on optoelectronic devices, have yet to be developed. Herein this study, a three-terminal flexible memory phototransistor (MPT) is first fabricated, which simulates the visual nociceptive behavior by adjusting light stimulation. The CsPbBr$_3$ quantum-dots (QDs)-few-layered black phosphorous cated, which simulates the visual nociceptive behavior by adjusting light types of sensors, nociceptors are one of the most important and reproducible properties of the human nervous system. Nociceptor is a crucial sensory neuron that recognizes harmful inputs and sends pain signals to the central nervous system to avoid injury; however, visual nociceptors, considered to be a key bionic function to protect eyesight based on optoelectronic devices, have yet to be developed. Herein this study, a three-terminal flexible memory phototransistor (MPT) is first fabricated, which simulates the visual nociceptive behavior by adjusting light stimulation. The CsPbBr$_3$ quantum-dots (QDs)-few-layered black phosphorous nanosheets (FLBP NSs) heterojunction MPT demonstrates high responsivity of $7.2 \times 10^{4}$ AW$^{-1}$ and high detectivity of $1.8 \times 10^{13}$ Jones due to the high absorption coefficient of CsPbBr$_3$ QDs materials and a high carrier transport property of FLBP NSs. Moreover, the proposed device can be used to emulate ultraviolet-stimuli-induced characteristics of visual nociceptors such as a threshold, no adaption, relaxation, allodynia, and hyperalgesia. It provides a new avenue for the realization of next-generation neural-integrated devices via its visual pain sense-perception abilities.

1. Introduction

The installation of functional sensory system is a significant barrier to the manufacture of humanoid robots.[1–8] Among various types of sensors, nociceptors are one of the most important and characteristic receptors that generate pain signals to prevent the body from danger.[9–12] Hardware implementation of light-modulated artificial nociceptor is the building block for an artificial visual system, which has been reported by emulating pain response to light signal stimulation.[13] Because of its high bandwidth and minimal cross talk, light-triggered device can provide a noncontact operative approach and may be a better option for increasing operating speed.[14–19] Nevertheless, a high-performance ultraweak light-modulated nociceptor that can be equipped with remote sensing, night vision, and astronomical observation has yet to be reported.

With the goal of constructing a weak light-modulated nociceptor, an optoelectronic memory device that incorporates memory with photodetector is a promising candidate owing to its multifunctionality, high-density, multilevel, and non-volatility.[20–26] Since a photon normally only excites one pair of electrons and holes which can be further trapped by the charge-trapping sites, these optoelectronic memory devices are usually based on the continuous photoconductivity effect or light-induced conductivity enhancement.[27–30] Utilization of heterostructured materials is an effective approach to form a potential barrier to separate photo-induced electrons or holes, accumulate photocarriers at the interface, and subsequently control the channel conductivity, allowing the simulation of ultraweak light-modulated nociceptor by the accumulation of optical signals.[31]

Black phosphorous (BP) is a promising candidate for optoelectronic applications owing to its unique anisotropic puckered structure and direct bandgap from 0.3 eV for bulk to 2 eV for monolayer. While quantum-structured CsPbBr$_3$ perovskites are currently at the focus of immense scientific attention in view of their astonishing optical properties. Recently, Ogle et al. demonstrated self-assembled CsPbBr$_3$ quantum dots (QDs) on BP nanostructures that exhibit effective charge transfer through I-type band arrangement.[32] A 0–2D few-layered black phosphorous (FLBP)-CsPbBr$_3$ nanocomposite exhibited broadband absorption from 400 to 1100 nm and quenched luminescence compared with pristine CsPbBr$_3$ QDs and FLBP nanosheets.
(NSs). Based on that, we first implemented a three-terminal flexible memory phototransistor (MPT) that shows nociceptive behavior with modulation of optical stimuli. The MPT utilizes the characteristics of heterojunction to facilitate the separation and generation of electron-hole pairs, ensuring its charge storage function and improved photodetection ability. Specifically, the holes created in the photoactive CsPbBr3 QDs-FLBP NSs layer are injected into semiconductor layer channels to increase the carrier concentration. For such a flexible MPT, a high responsivity of $7.2 \times 10^4 \text{AW}^{-1}$ and detectivity of $1.8 \times 10^{13} \text{Jones}$ can be achieved. Moreover, this MPT can be used to emulate characteristics of photonic nociceptor including threshold, no adaption, and relaxation along with allodynia and hyperalgesia in response to light-induced stimuli. Therefore, light-induced nociceptive behavior in our MPT has a high response rate (0.05 s), which reduces the heat created during operation and allows for high integration.

2. Results and Discussion

CsPbBr3 QDs and FLBP NSs were synthesized according to the previously reported method (see the experimental part in the supporting information for details). First, we prepared CsPbBr3 QDs (thermal injection method) and FLBP NSs (probe ultrasonic method) separately, then mixed them in a certain proportion, and finally sonicated the mixture to realize the self-assembly of CsPbBr3 QDs on the surface of FLBP NSs (Figure 1a). The challenge of solution preparation is to choose a suitable universal solvent for both CsPbBr3 QDs and FLBP NSs to ensure self-assembly. We prepared FLBP in $N$-methyl-2-pyrrolidone (NMP) solvent and then performed multiple centrifugal separation and generation of electron-hole pairs, ensuring its charge storage behavior in our MPT has a high response rate (0.05 s), which reduces the heat created during operation and allows for high integration.

The CsPbBr3 QDs-FLBP NSs MPT device was constructed on atomic layer deposition (ALD)-deposited Al2O3 (30 nm)/Si substrate. The typical three-dimensional structure and cross-sectional scanning electron microscope (SEM) of CsPbBr3 QDs-FLBP NSs MPT are illustrated in Figure 2a,b, respectively. In our case, the CsPbBr3 QDs-FLBP NSs composite film was utilized as both the floating gate and light-sensing layer for memory phototransistor, which interfaces with the pentacene semiconductor layer (30 nm), and 30 nm Au electrodes were served as source and drain electrodes. The SEM and atomic force microscope (AFM) image of self-assembled heterojunction fabricated with different concentrations of CsPbBr3 QDs (0.5, 1.0, 1.5, and 3 mg mL$^{-1}$) is presented in Figure S3 and S4, Supporting Information, from which it can be seen that the distribution of CsPbBr3 QDs on FLBP NSs becomes denser with the increase of concentration. The transfer characteristics of the devices based on the heterostructure with different concentrations of CsPbBr3 QDs are described in Figure S6, Supporting Information. As the CsPbBr3 QDs concentration increases, the memory window changes from 0.4 to 0.5, 0.6, and 1.2 V. When the concentration of CsPbBr3 QDs is 1.5 mg mL$^{-1}$, the largest memory window can be obtained, so we choose it as the optimal concentration. We further compared the performance of the CsPbBr3 QDs-based and CsPbBr3 QDs-FLBP NSs-based MPT, respectively. Figure 2c,d illustrates the optical programming after the irradiation of a 365 nm laser with an intensity of 0.069 mW cm$^{-2}$ and electronic erasing operation under the $-5$ V pulse of the two devices. As shown in Figure 2d, the memory window of CsPbBr3 QDs-FLBP NSs MPT increases significantly compared with CsPbBr3 QDs MPT. In this structure, the light induces electron transfer from the photoexcited CsPbBr3 QDs to FLBP NSs. Then the injected electrons will be stabilized in FLBP NSs owing to their large surface area and high carrier mobility, resulting in the accumulation of electrons on FLBP NSs and the formation of the internal electric field. The larger threshold voltage ($V_{th}$) shift of CsPbBr3 QDs-FLBP NSs MPT suggests that the injection of...
electrons in the FLBP NSs can be adjusted by UV light, and when the voltage of −5 V is used to erase, the transfer curve can be reset to its initial state, indicating that the electrons generated by the light can escape from the FLBP NSs under electrical field.

The relationship between the light intensity, current level \( \frac{I_{ON}}{I_{OFF}} \), and \( V_{th} \) is shown in Figure 2e, showing the statistical switching uniformity and stability. In the 1000-cycle test, the spatial uniformity of the photon-mediated resistance switch was further verified (Figure 2h). The optically programmed state of \( \text{CsPbBr}_3 \) QDs-FLBP NSs MPT shows spatial uniformity with device-to-device variability of 0.458. The electrically erased state shows spatial uniformity with inter-device variability of 0.524. Additionally, Figure S7, Supporting Information depicts the output curve of devices under dark and UV illumination. Under dark conditions, the characteristics of p-type transistors can be verified by linearity and saturation regions of current. The current of MPT increases significantly under light irradiation (0.163 mW cm\(^{-2}\)), indicating the increased hole density in the semiconductor channel. Under low \( V_{DS} \), the linear output characteristics indicate that an ohmic contact is achieved at the pentacene-Au electrode interface (Figure S7a, Supporting Information).

Then, we investigated the transient response of the \( \text{CsPbBr}_3 \) QDs-FLBP NSs MPT under UV light illumination (0.0126 mW cm\(^{-2}\)) for 50 ms (shown in Figure 2f). The photocurrent of \( \text{CsPbBr}_3 \) QDs MPT rises from 30 up to 82 nA while...
the photocurrent of CsPbBr$_3$ QDs-FLBP NSs MPT reaches 108 nA within 50 ms. The high speed of light-induced charge trapping is originated from the photovoltaic and photogating effect of heterojunction, ensuring the ultra-fast reading and writing by optically adjusting the interface energy level of the heterojunction. In addition, the readout current of CsPbBr$_3$ QDs-FLBP NSs MPT and CsPbBr$_3$ QDs MPT following optical pulses treatment (0.069 mW cm$^{-2}$) is compared in Figure 2g. The optically programmed current of CsPbBr$_3$ QDs-FLBP NSs MPT could be kept in a highly conductive state, while the current of CsPbBr$_3$ QDs MPT decreased sharply, indicating that the heterojunction could retain the trapped charge carrier within the Schottky barrier.

In artificial visual systems, the transition from short-term memory (STM) to long-term memory (LTM) based on continuous light perception is a necessary condition for the realization of advanced imaging functions. First, by changing the intensity and width of the light stimulus, the biological function of this CsPbBr$_3$ QDs-FLBP NSs MPT transition from STM to LTM was successfully explained. The simulation of the enhancement of short-term and long-term forms by optical stimulation with intensity ranging from 0.041, 0.069, 0.126 to 0.163 mW cm$^{-2}$ as illustrated in Figure 3a. When a low-intensity (0.041 mW cm$^{-2}$, duration: 5 s) pulse is applied, the pentacene channel cannot maintain the triggered high-conductivity state and gradually decays back to its initial state, which is similar
to the STM mechanism of memories. In comparison, when the input pulse intensity increases to 0.069, 0.126, and 0.163 mW cm$^{-2}$, the optical CsPbBr$_3$ QDs-FLBP NSs MPT also performs a permanent transition to a high-conductivity state, simulating LTM behavior. This is due to a deeper photo-generated electron capture event resulting in a long-term increase in channel conductance. Similarly, Figure 3b describes STM and LTM characteristics are realized by varying the light stimulus

Figure 3. Correlation between film charge-trapping behavior and optical visual memory emulation properties of CsPbBr$_3$ QDs-FLBP NSs MPT. a, b) short-term memory (STM) or long-term memory (LTM) formation in the photonic synapse depending on a) input-photonic-pulse duration (duration: 5 s) and b) intensity (intensity: 0.126 mW cm$^{-2}$). c) Pulse-frequency-dependent photoresponse of the device (intensity: 0.069 mW cm$^{-2}$). d) Schematic diagram of nanoscale current harvesting via conductive atomic force microscope (C-AFM). The Al$_2$O$_3$/CsPbBr$_3$ QDs-FLBP NSs/pentacene thin film is spin-coated on a heavily doped silicon wafer. The AFM tip slides in contact mode on the sample surface, which induces electronic excitation and carrier conduction. e) Surface potential profile recorded of the Al$_2$O$_3$/CsPbBr$_3$ QDs-FLBP/pentacene film before and after different illuminate power ranging from 0.041 to 0.163 mW cm$^{-2}$ was recorded by in-situ AFM electrical nanotechnology. The image on the right is a surface potential difference under different intensity power. f) Band diagram of the CsPbBr$_3$ QDs-FLBP NSs MPT and photocarriers transfer under laser illumination. g) Kelvin probe force microscopy (KPFM) image of the CsPbBr$_3$ QDs-FLBP NSs film after electrons injection through the incrementally increasing voltage applied to the tip under dark and under 365 nm illumination with 0.069 mW cm$^{-2}$. 
length. The frequency of stimulation with memorizing devices can be proposed to further understand the optical transition behavior. As illustrated in Figure 3c, ten pulses with the frequency varying from 1 to 20 Hz (or the pulse interval is changed from 1 to 0.05 s) were applied to CsPbBr$_3$ QDs-FLBP NSs MPT. When the frequency is set to 1 Hz, the current does not increase substantially, but when the frequency is raised to 20 Hz, the current increases by more than 30 times, the earlier results thus strongly indicate that the optical sensing and memory abilities can be greatly enhanced in our CsPbBr$_3$ QDs-FLBP NSs MPT device as the light frequency increases. The photocative response is related to the charge-trapping behavior in the heterojunction under optical modulation, which is verified by monitoring the electrostatic force, surface potential, and carrier-trapping behavior via the Kelvin probe force microscopy (KPFM) (Figure 3d). The average surface potential gradually increases as the incident light intensity increases to reach a maximum of 10$^3$ under 0.163 mW cm$^{-2}$, indicating excellent photosensitivity of our MPT. Phototransistor also has two major variables: photosensitivity (R) and photodetectivity (D*). R is defined as $R = I_{ph}/(P_{inc}S)$, indicating how efficiently the phototransistor responds to light, where $I_{ph}$ is the photocurrent, $P_{inc}$ is the incident light intensity, and $S$ is the device’s channel area. $D^*$ denotes the capability of the phototransistor to detect weak optical signals and can be calculated using the following expression:

$$D^* = (A^{1/2} R)/(2qI_d)^{1/2},$$

where $q$ is the elementary charge and $I_d$ is the dark current. The representative $R$ and $D^*$ values as functions of irradiation and $V_{GS}$ are presented in Figure 4d,e. When $V_{GS}$ is $-5$ V and the optical power is 0.041 mW cm$^{-2}$, $R$ reaches the maximum value of 7.25 x 10$^7$ AW$^{-1}$, which is much larger than the recently reported heterostructure-based photodetectors as shown in Table 1. $D^*$ has a similar tendency to $I_{photo}/I_{dark}$, reaching a peak when the voltage applied to the gate is $-1$ V. We can realize that the $D^*$ peak of our MPT under irradiation is above 10$^{15}$ Jones, and the maximum $D^*$ reaches 4.2 x 10$^{13}$ Jones at $V_{GS}$ is $-1$ V. Furthermore, changing the threshold voltage provides a practical approach for characterizing the phototransistor’s photoresponse. Voltage responsivity ($R_v$) can also be utilized to evaluate the photoresponse of a phototransistor and is defined as follows: $R_v = \Delta V_{th}/PA$, where $\Delta V_{th}$ is the shift threshold voltage after the light irradiation. Figure 4f illustrated the threshold voltage variation as a function of light intensity. The absolute value of the threshold voltage shift increases with increasing light intensity, but it tends to saturate under high intensity. As shown in Figure 4g-i, the uniformity of the $R$, $D^*$, and $R_v$ characteristics were examined by measuring 30 devices. CsPbBr$_3$ QDs-FLBP NSs MPT exhibits both higher photocurrent and photosensitivity compared with conventional optoelectronic and hybrid optoelectronic devices. In addition to the optical power perception behavior illustrated earlier, the wavelength-dependent effect of the CsPbBr$_3$ QDs-FLBP NSs MPT improves the vision system’s intrinsic light sensitivity and color selectivity, which improves the device’s perception accuracy. The stability of our devices was investigated under different wavelength and low-temperature conditions over time as shown in Figure S13, Supporting Information. When the wavelength is decreased from 660 to 365 nm, the device’s switching current ratio rises from $2.8 \times 10^3$ to $5.6 \times 10^3$. Apart from its high-performance photodetection, our MPT also exhibits good environmental stability. We tested the transfer characteristic curves (light intensity: 0.069 mW cm$^{-2}$, duration: 1 s) and electrical erasing operations of the CsPbBr$_3$ QDs-FLBP NSs MPT device in the atmospheric environment for at least one week. The optoelectronic devices show that the original memory window (1.2 V) will be preserved during this period (Figure S14, Supporting Information), indicating good stability.

The CsPbBr$_3$ QDs-FLBP NSs MPT device in the atmospheric environment for at least one week. The optoelectronic devices show that the original memory window (1.2 V) will be preserved during this period (Figure S14, Supporting Information), indicating good stability.
Figure 4. Photodetection performance of CsPbBr₃ QDs-FLBP NSs MPT. a) Transfer characteristics of the CsPbBr₃ QDs-FLBP NSs phototransistor measured in the dark after it was irradiated with light intensities from 0.041 to 0.163 mW cm⁻² (duration:1 s). b) Photocurrent as a function of V_G and light intensity. c) Photosensitivity of the CsPbBr₃ QDs-FLBP NSs MPT at different gate voltages and different light intensities. d,e) R and D* as functions of MPT under different light intensities at V_G = −1 V and −5 V. f) ΔV_th, R_V characteristics of the device at V_G = −1 V. g–i) Statistical variability of R, D*, and R_V of 30 devices. The drain voltage used in this section was −1 V.

Table 1. Performance summary of previously reported perovskite-2D-based phototransistor.

| Material                        | Thickness [nm] | D* [Jones] | Wavelength [nm] | Reference |
|--------------------------------|----------------|------------|-----------------|-----------|
| PbS QD/MoS₂                     | 40–60          | 5 × 10¹¹   | 980             | [36]      |
| CsPbBr₂/MoS₂                    | >100           | 2.5 × 10¹⁰ | 442             | [37]      |
| Perovskite/MoS₂                 | >100           | 1.2 × 10¹⁰ | 520             | [38]      |
| CH₃NH₃PbI₃/MoS₂                 | >100           | 2.6 × 10¹⁰ | 500             | [36]      |
| perovskite/BP/MoS₂              |                | 1.3 × 10¹² | 457             | [39]      |
| PbS QD/graphene                 | 30–50          | 5.5 × 10¹² | 637             | [39]      |
| PbS QD/graphene                 | 100            | 7 × 10¹³   | 600             | [40]      |
| MAPbBr₃/graphene                | >100           | 1 × 10⁹    | 400–800         | [41]      |
| CH₃NH₃PbI₃/WSe₂                 | >100           | 2.2 × 10¹² | 532             | [42]      |
| CH₃NH₃PbI₃/WS₂                  | >100           | 2 × 10¹²   | 505             | [43]      |
| CsPbBr₃ quantum-dots/few-layered black phosphorous nanosheets (QDs/FLBP NSs) | 10–20          | 1.8 × 10¹³ | 365             | This work |
strain = \frac{d}{(2r + d)}, \text{ where } d \text{ is the thickness of the PET film, and } r = 10 \text{ mm. When the strain is less than 1\% (r > 5 mm), the device’s photocurrent degrades by less than 5\%. Following that, we explored the effect of under-strain states on the photodetection capability of the CsPbBr_3 QDs-FLBP NSs MPT as illustrated in Figure 5c–e, and Figure S17, Supporting Information. There is almost no change in its photosensitivity, while the photoresponsivity and photodetectivity have a slightly decreasing trend under the compression/extension strain state. As can be seen, the depression is less than 8\% under the condition of 1\% strain, demonstrating the film’s exceptional photodetection durability.}

Through the optical memory and photodetection characteristics of the CsPbBr_3 QDs-FLBP NSs MPT, we have confirmed that the e–h pair generated by the photocurrent is filling the trapped state, thereby producing relatively smooth conduction. Simultaneously, it is observed that the current of the device is close to saturation, indicating that it can be utilized to design light-triggered visual nociceptors. When neurons at free nerve terminals are stimulated, they generate an electrical signal and transmit it to the nociceptors. The visual nociceptors compare the signal’s amplitude to its threshold to determine whether or not to generate an action potential and transmit it to the brain via the central nervous system (Figure 6a). It not only exhibits the threshold switching and relaxation dynamics observed in normal neurons in response to noxious stimuli, but also exhibits its characteristic properties such as “no adaptation,” “allodynia,” and “hyperalgesia” in response to repeated stimuli and excessively intense stimuli, respectively.[9–11] The trigger of biological nociceptors is dependent on duration, intensity, and the number of stimuli. Therefore, we replicate external stimulation of our nociceptors by using light pulses with varying amplitudes, pulse widths, and pulse counts. We set the threshold of the CsPbBr_3 QDs-FLBP NSs MPT to 60 nA. The MPT cannot be switched on until the light intensity reached 0.069 mW cm^{-2} under single light pulse with width of 0.5 s. When the light intensity increases further to 0.163 mW cm^{-2}, the output current increases significantly (Figure 6c). Similarly, under a fixed light intensity (0.069 mW cm^{-2}), we observed that sufficiently long pulse width (0.5 s) is necessary to reach the threshold value for our MPT (Figure 6d), and a longer pulse width results in a larger output current. To further validate the device’s threshold properties, the light response was tested under self-biased conditions by varying the pulse intensity from 0 to 0.069 mW cm^{-2}, as shown in Figure 6f. Interestingly, the device did not exhibit a significant photosresponse at intensities less than 0.006 mW cm^{-2}, but the photocurrent progressively increases and reaches saturation when exposed to continuous light pulses (intensities larger than 0.02 mW cm^{-2}). After attaining saturation, even if additional pulses are applied, the photocurrent remains constant, indicating that the device’s reaction is constant when the same stimulus is applied repeatedly. It is worth noting that once a balance is struck between the generation and capture of light-generated e–h pairs, the photocurrent flowing through the device remains constant, even after repeated illumination.

Figure 5. Flexible characteristics of the CsPbBr_3 QDs-FLBP NSs MPT. a) Schematic and photograph of the CsPbBr_3 QDs-FLBP NSs MPT array fabricated on a flexible polyethylene terephthalate (PET) substrate. b) Vth and ION/OFF distribution of flexible memory phototransistor under different bending cycles (programming light intensity:0.069 mW cm^{-2}, erasing electrical voltage:−5 V). c) Photocurrent, d) R, and e) D* measured under tensile and compressive strain conditions at different light intensity pulses. The drain voltage used in this section was −1 V.
pulses. This phenomenon is similar to the nonadaptive characteristics of pain receptors, which is essential for the human body or humanoid robots to protect themselves from repeated harmful stimuli.

Apart from the threshold and nonadaption behavior, relaxation is another important nociceptive characteristic. As shown in Figure 6e, pulse measurements were taken at various intervals (0.5, 1, and 2 s). We activated the device with the first light pulse (0.069 mW cm⁻²) and then applied the second light pulse (0.069 mW cm⁻²) at a different interval. However, when the identical stimulus is administered prior to the complete relaxation of the device, a considerable current response is recorded.
(black and red curves in Figure 6e). Additionally, the other primary properties of nociceptors, alldynia, and hyperalgesia were further examined. When a powerful enough stimulus is provided to the nociceptor, the nociceptor will be in an injured state. After the injury, the nociceptor will exhibit an amplified reaction when the threshold is lowered, referred to as alldynia and hyperalgesia (Figure 6b). In this work, an injured state is induced using high ultraviolet (HUV) and low ultraviolet (LUV) pulses. Prior to HUV illumination, “no injury” nociceptors originally responded poorly to low photocurrent values. Following exposure to HUV, the nociceptors are “injured,” the injured nociceptor becomes more sensitive, and the photocurrent as a function of the light intensity is expressed in linear (Figure 6g) and logarithm scale (Figure 6h). This demonstrates that a lower threshold light intensity is required to activate a device capable of simulating the “alldynia” and “hyperalgesia” properties of nociceptors. As a result of the preceding study, it is clear that our MPT device can emulate the visual nociceptor properties of “threshold”, “relaxation”, “non-adaptation”, “alldynia”, and “hyperalgesia.”

3. Conclusion

We have proposed an artificial visual nociceptor based on a CsPbBr3 QDs-FLBP NSs memory phototransistor, which realizes all the key functions of the nociceptor in a single device, including threshold, relaxation, no adaptation, alldynia, and hyperalgesia. Not only that, the MPT device also has excellent optical memory and optical detection capabilities, which use the mechanism of adding light to promote the separation and generation of heterojunction electron-hole pairs. The new artificial nociceptor can easily be extended from light stimulation to processing other stimuli, such as chemical, mechanical, etc., showing the potential application of integrating optoelectronic circuits and artificial intelligence receptors on the chip.

4. Experimental Section

Material Preparation: All chemicals were purchased from Sigma Aldrich without further purification: barium carbonate (Cs2CO3, 99.9%), lead bromide (PbBr2, 99.99%), oleic acid (OA, technical grade, 90%), 1-octadecene (ODE, technical grade, 90%), oleylamine (OAm, technical grade, 70%), hexane (anhydrous, 98%), toluene (anhydrous, 98%), and methyl acetate (MeOAc, anhydrous, 99.5%).

Preparation of Cs-Oleate: The CsPbBr3 QDs were effectively synthesized according to the procedure reported by Proteescu et al.[23] The ruthenium oleate precursor was synthesized by loading 0.81 g of Cs2CO3, 40 mL of ODE, and 2.5 mL of OA to 100 mL of 3-necked flask, and then heating to 120 °C for 1 h under a nitrogen atmosphere to ensure complete reaction of Cs2CO3 with OA. The prepared solution was maintained at 160 °C to avoid further precipitation. Finally, transparent solution was observed and it was preheated at 100 °C.

Synthesis of CsPbBr3 QDs: Five milliliters of ODE mixed with 0.188 mmol of PbBr2 was placed in another 3-necked flask, and the temperature was maintained at 120 °C for 60 min under vacuum, and 0.5 mL of oleylamine (technical grade, 70%) and 0.5 mL of OA were injected, and the temperature was increased to 140 °C under a flow rate of N2. Immediately, 0.4 mL of the yttrium oleate precursor was injected into the flask. The solution turned to fluorescent green, and the flask was immersed in an ice/water bath for quenching 5 s after hot injection.

Purification of CsPbBr3 QDs: The purification of CsPbBr3 QDs was performed by following the previous report by Swarnkar et al.[24] QDs of as-synthesized CsPbBr3 precipitated in 15 mL of MeOAc and then centrifuged at 9000 rpm for 5 min. In addition, the CsPbBr3 QDs of each centrifuge tube were wet pellets in 1 mL of redispersed hexane with the same volume of MeOAc and precipitated at 9000 rpm for 5 min. QDs were redispersed in 2 mL of anhydrous toluene or hexane.

Purification of FLBP: Using BP crystals as raw materials, low-layer BP was prepared by the probe method in NMP solvent.[25]

Preparation of Self-Assembled CsPbBr3 QDs-FLBP NSs: Through the solvent exchange of toluene, the self-assembly of CsPbBr3 QDs on FLBP was realized. First, CsPbBr3 QDs solution of different concentrations (0.5, 1, 1.5, 3 mg mL−1) was adopted, then, FLBP with a concentration of 0.5 mg mL−1 was added, and finally it was bathed in ultrasound at room temperature.

Fabrication of Flexible CsPbBr3 QDs-FLBP NSs Memory Phototransistor: The CsPbBr3 QDs-FLBP MPT was manufactured with a bottom-gate top-contact structure on a PET/indium tin oxides (ITO)/Al2O3 substrate. Strip ITO was evaporated onto the PET layer as a gate by thermal evaporation. Then 30 nm dielectric layer Al2O3 is deposited on PET/ITO by ALD under 80 °C. After that, the CsPbBr3 QDs-FLBP was spin-coated onto the Al2O3 surface at a speed of 3000 rpm for 40 s, followed by annealing with 100 °C for 15 min in a glove box. Next, under 4 × 10−4 Pa, p-type 30 nm pentacene semiconductor layer was thermally evaporated (rate: 0.1 Å s−1) on the top of the CsPbBr3 QDs-FLBP charge-trapping layer. Finally, 30 nm Au source and drain electrodes were thermally evaporated on the pentacene film via a shadow mask. And the channel length for the as-prepared memory device was 50 μm.

Characterizations and Measurements: PL spectra were conducted on an Edinburgh Instruments (FLS 920). And the UV-visible spectra were recorded on an UV-visible spectrophotometer (Agilent Cary 60). The prepared CsPbBr3 QDs-FLBP were characterized by HR-TEM (Tecnai F30). All nanoelectronic measurements were made at room temperature using the Bruker size icon AFM. SCM-PIT (which is a type of electrical force modulation AFM probe) was used to measure the top surface distance of all samples was measured at a surface distance of 75 nm (resolution: 256 × 256 pixels), and the charge-trapping ability of pentacene thin films was studied by AFM technique in combination with contact mode and KPFM mode. There are two steps for each measurement: two-dimensional charge injection and surface potential measurement. First, in the contact mode, the scan rate of 0.8 Hz, the 6 V bias was a technique applied to the injection of conductive electrons (scan area: 1 × 1 μm; resolution: 256 × 256 pixels). Injection of the well was achieved by biasing the tip of a 5 V at different scanning zones. Then, the AFM system was converted to KPFM amplitude modulation mode for on-site surface potential measurement. Scan, scan rate 10 × 10 μm 0.8 Hz, respectively. What’s more, the top surface distance of all samples was measured at a surface distance of 75 nm (resolution: 256 × 256 pixels), and the electrical characteristics of all devices were measured using the Keysight B2902A Precision Source/Measurement Unit and the Keysight 4200-SCS Parameter Analyzer. All device tests were performed at room temperature.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
CsPbBr3 QDs, FLBP, memory, phototransistors, visual nociceptors

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