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ABSTRACT

Artificial iconic memories, also called photomemories, are new types of nonvolatile memory that can simultaneously detect and store light information in a monolithic device. Several approaches have been proposed to construct artificial iconic memories, such as three-terminal field effect transistors, which can achieve an effective control of the gate voltage and external light terminals. The drawbacks in constructing these memories involve complicated fabrication processes, and the resulting performance of, for example, perovskite transistor-type photomemories is limited by the low carrier mobilities and poor ambient stabilities, whereas architectures based on floating gate modulations entail strict interface engineering and poor device reliability. In this paper, we propose a novel monolithic artificial iconic memory with a multilayer architecture of indium tin oxide/perovskite/gold/perovskite/silver, which combines the memory and photodetector functionalities of perovskites in an integrated device. The bottom perovskite layer plays the role of a photodetector, modulating the voltage bias on the top perovskite layer that serves as a resistive switching memory. This multilayer perovskite device can store photo-sensing data in its resistive states, with a memory retention of 5×10^3 s and ambient stability longer than sixty days. As a prototype demonstration, a 7×7 artificial iconic memory array is constructed to detect and store data on light intensity distribution, enabling a nonvolatile imaging functionality. Our work provides a new platform for designing perovskite-based architectures with simultaneous light detection and data storage capabilities.

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I. INTRODUCTION

Artificial sensory memory, which incorporates the sensor and memory components in one electrical device to mimic the biological sensory neuron, has drawn great attention in the last decade within the overall context of artificial intelligence (AI) development.^{1–3} By integrating the receptor-like exquisite sensing capabilities and synapse-like memory capabilities, artificial sensory memory can serve as the building block for constructing new hardware architecture of autonomous AI, with direct access to sensory data and information storage, simultaneously.¹ For human beings, the eye is an essential organ, and almost half of the cerebral cortex is related to vision data processing, which helps us to appreciate the world better.⁴ For AI

applications, artificial iconic memory, which refers to the memory of visual stimuli and is one of the important members in the artificial sensory memory family,¹ however, has not been widely studied compared with its counterparts, such as artificial haptic memory, artificial nociceptive memory, and so on.

Artificial iconic memory synergetically merges the functionalities of the photodetector and nonvolatile memory. A conventional photodetector can only record a transient optical signal, and additional memory devices are needed to further store the output data from the photodetector. In this context, artificial iconic memory, also called visual memory⁵ or photomemory,^{6,7} is emerging as a new type of nonvolatile memory that can simultaneously detect and store light

information in a monolithic device. Compared with the conventional memory device based on electric programming, photon stimulation is not only faster due to the high speed of light but also provides a non-contact writing process, which helps to improve the device stability and simplifies the device configuration.⁸

Several approaches have been proposed to construct artificial ionic memories. First of all, the three-terminal field-effect transistor (FET) is the most popular scheme because of the effective control of gate voltage and an external light terminal. In recent years, organic compounds,^{7,9–13} halide perovskite,^{6,14–16} and two-dimensional (2D) materials^{17–20} have already demonstrated their applications in the photomemory field via the transistor structure. Second, rationally integrating resistive switching (RS) memories and sensor devices can achieve long-term ionic memory. In a representative work, Chen *et al.* fabricated an artificial visual memory based on a series-connected In_2O_3 photodetector and $\text{Ni}/\text{Al}_2\text{O}_3/\text{Au}$ memristor.⁵ UV light was able to reduce the resistance in the photodetector, which led to the increase in partial voltage on the tandem memory and stored the light information. Finally, an artificial ionic memory can be achieved by leveraging on the intrinsic physical properties of materials. Very recently, Zou *et al.* fabricated a nonvolatile rewritable photomemory array based on the reversible phase-change property of CsPbIBr_2 .²¹ The phase transition of CsPbIBr_2 between orthorhombic and cubic phases was achieved through laser-induced heat and moisture exposure.

However, there are still drawbacks to the existing approaches. For example, artificial ionic memory adopting the conventional three-terminal FET configuration involves a complicated fabrication process,^{6,14,15} and the performance of perovskite transistor-type photomemory is generally limited by the low carrier mobility and poor ambient stability, and architectures such as floating gate modulation entail strict interface engineering,^{6,14} leading to poor device reliability.²² Besides, the material choice can limit the applications and the wavelength range of artificial ionic memories. For example, some published works adopt wide-bandgap semiconductors, which only respond to high-energy UV light.⁷ Also, the operation of the photomemory, as

mentioned earlier, based on CsPbIBr_2 phase transition, requires an infrared laser.²¹ Another challenge is the difficult device integration due to exfoliation of 2D materials^{17,18} and manipulation of nanowires,⁵ which leads to unreliable device processing and operation.

Compared to organic and 2D materials, hybrid methylammonium lead halide perovskites (MAPbX_3 , X: I, Br, Cl, or their mixtures) possess superior physical properties, like low trapping density,²³ ambipolar charge transport,²⁴ tunable visible bandgaps,²⁵ solution-processability,^{26,27} and long diffusion length,^{23,28} which make them highly competitive for a wide range of optoelectronics applications, including solar cells,^{29–31} photodetectors,^{32–38} lasers,^{39–42} and transistors.^{43–45} As a novel semiconductor, hybrid perovskites can serve as both sensor and memory, which makes them suitable for fabricating monolithic artificial ionic memories. Since 2015, there have been pioneering works on using perovskites in RS devices.^{26,46–48} However, most of the reports only present the conventional electric programming performance while ignoring the photo-sensing capability of perovskites.⁶

Herein, we report on the design and fabrication of a new type of artificial ionic memory device with a perovskite/metal multilayer architecture of indium tin oxide (ITO)/ MAPbBr_3 /Au/ MAPbBr_3 /Ag. The bottom ITO/ MAPbBr_3 /Au sandwich serves as a photodetector, and light illumination modulates the voltage distribution, which controls the resistive states of the top Au/ MAPbBr_3 /Ag RS device. Due to the intrinsic properties of MAPbBr_3 (MPB) prepared by vapor deposition and the metal-interfaced multilayer device structure, our artificial ionic memory is stable in ambient conditions and remains functional for more than two months. Furthermore, the artificial ionic memory arrays could clearly detect and memorize spatial light intensity distribution, as demonstrated by a prototypical imaging array. Such perovskite/metal multilayers provide a new platform for designing architectures with simultaneous light detection and data storage capabilities.

II. RESULTS

The design and configuration of the artificial ionic memory are shown in Fig. 1. As universal components, a photodetector receives

FIG. 1. (a) Schematic diagram of constructing a monolithic artificial ionic memory based on a photodetector and a RS memory, which serve to simulate human eyes and brain, respectively. Φ_L and Φ_E represent light flux and electric flux, respectively. As universal components, a photodetector receives the light flux and converts it into photocurrent, while a memory changes its resistance states due to electric flux and charge accumulation, which is related to the current via the time derivative $I = dQ/dt$. (b) Schematic diagram of the artificial ionic memory arrays with ITO/MPB/Au/MPB/Ag structure. Our monolithic artificial ionic memory design illustrated here simply integrates one photodetector and one resistive switching memory in a unique multilayer stack. Inset illustrates the integration of photodetector and RS device in the monolithic artificial ionic memory.

the light flux and converts it into photocurrent, while a memory changes its resistance states due to electric flux and charge accumulation, which is related to the current via the time derivative $I = dQ/dt$ [Fig. 1(a)].⁴⁹ In the previously reported design of artificial iconic memory, nonvolatile memory function is realized by charge storage at the interface defects through the light-controlled trapping/de-trapping process in FET structures, which requires precise control of the semiconductor-dielectric-metal interface with appropriate energy offsets.⁶ In contrast, our monolithic artificial iconic memory design illustrated in Fig. 1(b) simply integrates one photodetector and one RS memory in a unique multilayer stack. Such a monolithic multilayer architecture has been demonstrated in an artificial haptic memory in 2015 by Zhu *et al.*,⁵⁰ in which a pressure sensor and a RS memory were integrated in series by replacing the bottom electrode of the pressure sensor with the electrode of RS memory. After inducing external pressures on the sensor, the resistance changes in the pressure sensor issued in the voltage changes on RS memory, leading to the resistance state change and memorizing the pressure information. In the present work, the resistance changes of the photodetector results from light stimuli, then leads to the memory of light information. The details of multilayer growth and device fabrication can be found in the experimental section. Basically, the patterned ITO and Au electrodes were thermally evaporated through a shadow mask with a width of 100 μm , forming the crossbar array, and the top Ag electrodes were deposited through an aligned shadow mask. It is worth mentioning that the perovskite films with a thickness of around 300 nm were deposited by a dual-source thermal evaporation method, which warrants very smooth interfaces and superior ambient device stability.²⁹ In this study, we used the same perovskite composition with similar thickness, which helps balance the resistances of the memory and photodetector components of the monolithic device as well as simplifies the fabrication process.

The detailed working procedure of the multilayer artificial iconic memory is illustrated in Fig. S1 (see the [supplementary material](#)). Since the photodetector and the memory are connected in series,⁵⁰ the mechanism of nonvolatile light detection is quite straightforward. Under dark conditions, the voltage bias between the top Ag electrode and the bottom ITO electrode is proportionally distributed on the photodetector and the RS memory according to their resistance ratio. In the beginning, the voltage shared by the memory is not large enough to convert the resistance state from high resistance state (HRS) to low resistance state (LRS). However, under light illumination, the voltage drop across the RS memory will abruptly increase due to the light-induced resistance decrease in the photodetector. Since perovskite is one of the most light-sensitive materials,⁵¹ almost all of the bias falls on the RS under light illumination, and the high bias is sufficient to cause the formation of the Ag filaments through redox reaction.⁵² Even after removing the light, the RS memory will retain the LRS due to the nonvolatile nature of the Ag filaments, thereby storing the information of light illumination history. A reverse bias resets the memory by rupturing the Ag filaments, and the artificial iconic memory returns to its initial state, ready to receive further light and voltage stimuli.

Figure 2(a) shows the schematic of multilayer perovskite-based artificial iconic memory arrays, and the photograph of the device is shown in Fig. S2 (see the [supplementary material](#)). We labeled the Ag, Au, and ITO electrodes as terminal 1, terminal 2, and terminal 3, respectively. The cross-sectional scanning electron microscopy (SEM) image in Fig. 2(b) shows the multilayer ITO/MPB/Au/MPB/Ag device

structure. We can clearly see that both top and bottom perovskite layers are highly crystalline and have the same thickness of approximately 300 nm. The morphology of such perovskite films grown by vapor evaporation agrees well with the previous results.^{46,53} The resistance of the two metal/MPB/metal junctions is largely determined by the band alignment between the semiconductor (MPB) and the metals (ITO/Au/Ag).⁴⁶ In general, Au forms an Ohmic contact with perovskite,⁵⁴ while ITO and Ag electrodes form a Schottky junction with the perovskite layers due to the lower work functions.⁴⁶ From the electrical measurement results, we found that the photodetector and the RS memory have comparable resistance, and the voltage distribution across them can be effectively tuned.

The SEM images [Fig. 2(c)] of the top and bottom layers presented smooth MPB surfaces without any pinhole, and no obvious difference was observed for the two layers, indicating that consistent high-quality perovskite films can be achieved using the vapor evaporation method. It is worth noting that solution processing would not allow the preparation of perovskite multilayers, and this is, to the best of our knowledge, the first time that such perovskite-metal multilayers are fabricated. As confirmed by atomic force microscopy (AFM) images [Fig. 2(d)], the perovskite films exhibit large grains, and the root mean square roughness for the top and the bottom layer is 26 and 21 nm, respectively, in a typical scanning area of 5 $\mu\text{m} \times 5 \mu\text{m}$.

The x-ray diffraction (XRD) pattern demonstrates peaks of the perovskite phase without other impurity peaks [Fig. 2(e)]. The sharp diffraction peaks indexed as (001), (002), and (003) indicate the expected cubic MPB phase with good crystallinity.^{46,55} Compared with the top MPB layer, the bottom layer presented a higher (001) peak, indicating slightly better crystallinity and orientation of the film quality due to the smooth ITO substrate. The absorbance and photoluminescence (PL) spectra measured with the excitation of a 532 nm laser are presented in Fig. 2(f). The PL peak and absorbance edge are located at 539 nm (2.3 eV), which is in accordance with the direct optical bandgap of MPB reported in previous literatures.^{56,57}

The electrical characterizations of the individual components of the artificial iconic memory device (i.e., the top memory and the bottom photodetector) are shown in Fig. 3. For the photodetector, the energy diagram of the ITO/MPB/Au sandwich structure is shown in Fig. 3(a). The Au electrode is widely used to form Ohmic contact with perovskite, while a Schottky junction is expected at the ITO/perovskite interface.⁴⁶ Figure 3(b) shows the current-voltage (I - V) characteristic measured in the dark and under illumination (470 nm, 10 mW/cm²). Because of the asymmetric electrodes, the photodetector is self-biased under illumination with a rectification ratio of around 10^3 and a nA-level dark current. It should be noted that the photodetector does not show any RS behavior because the bias is not high enough to induce significant I - V hysteresis (Fig. S3, see the [supplementary material](#)).^{46,58} Figure 3(c) displays the switching of the device under a positive bias of 0.5 V, and no performance degradation was observed. It should be mentioned here that the performance of the photovoltaic-type photodetector can be further improved by inserting hole/electron transporting layers to reduce the charge recombination and dark current density.⁵⁹ The high resistance ratio ($\approx 10^3$) shown in Fig. 3(c) warrants that almost all the applied bias will drop across the memory under illumination to trigger the RS.

A typical I - V curve of the Au/MPB/Ag cell (top RS device) is shown in Fig. 3(d), and the corresponding I - V curve in linear scale is

FIG. 2. (a) Schematic illustration of the monolithic multilayer artificial ionic memory. (b) Cross-sectional SEM image of the ITO/MPB/Au/MPB/Ag structure in false color. The scale bar is 600 nm. (c) SEM image of the top MPB layer (upper half) and the bottom MPB layer (lower half). The scale bar is 500 nm. (d) AFM image of the top MPB layer (upper half) and the bottom MPB layer (lower half). The scale bar is 1 μm . (e) XRD pattern of the top and the bottom MPB thin films. (f) UV-vis absorption spectrum (green line) and photoluminescence spectrum (red line) of the MPB thin film.

shown in Fig. S4 (see the [supplementary material](#)). Reliable bipolar switching was observed in the device.⁶⁰ Initially, the device was in HRS with current levels of nA, which is consistent with the dark current of the bottom photodetector. The current abruptly increases by sweeping voltage to 0.5 V, and the device retained its LRS with a current level of μA for subsequent sweeps. We measured the RS characteristics of 49 devices, and the average ON/OFF ratio of the RS is 1.6×10^3 . The average set and reset voltage are 0.54 V and -0.69 V, respectively, as shown in Fig. S5 (see the [supplementary material](#)). Data retention characteristics of HRS and LRS values were measured with a reading bias (V_{read}) of 0.15 V [Fig. 3(e)]. A constant ON/OFF ratio more than 10^3 was maintained even after 10^4 seconds. Figure 3(f) depicts the cycling endurance test measured at $V_{\text{read}} = 0.15$ V. ON/OFF ratios above 10^3 were maintained for over 300 cycles. This bipolar RS characteristics of the device can be attributed to the formation and annihilation of Ag filaments.^{52,61} As illustrated in Fig. S6 (see the

[supplementary material](#)), the applied positive bias on Ag causes the dissolution of the Ag electrode by oxidation, and the generated Ag cations migrate under the applied electric field in the MPB layer. With the reduction of the Ag cations and nucleation above supersaturation, spontaneous growth of metal filaments occurs and leads to LRS. By applying reverse potential, disruption of the filaments occurs due to Joule-heating-assisted dissolution, and the HRS is recovered.

The monolithic multilayer perovskite artificial ionic memory demonstrated reliable responses to both light and electric stimulations. Figure 4(a) shows the I - V curves of the RS memory (between terminals 1 and 2) after exposing the artificial ionic memory to light illumination with different durations. During the light illumination (i.e., the setting process) a constant bias of 0.6 V was applied between terminals 1 and 3 [Fig. 2(a)]. As expected, the RS memory remained in the HRS during the voltage sweeping if there was no light illumination ($t = 0$ s) during the time of the setting process since the bias on the RS memory

FIG. 3. Photodetector and RS characteristics of the bottom ITO/MPB/Au and the top Au/MPB/Ag junctions, respectively. (a) Energy diagram of the ITO/MPB/Au photodetector. The Au electrode is widely used to form Ohmic contact with perovskite, while a Schottky junction is expected at the ITO/perovskite interface. (b) I-V curves of the bottom ITO/MPB/Au junction (i.e., the photodetector), with and without light illumination. The light wavelength is 470 nm. Because of the asymmetric electrodes, the photodetector is self-biased under illumination with a rectification ratio of around 10^3 and a nA-level dark current. It should be noted that the photodetector does not show any RS behavior because the bias is not high enough to induce significant I-V hysteresis. (c) Photoresponse under light pulses measured under a positive bias of 0.5 V. The high resistance ratio ($\approx 10^3$) shown in here warrants that almost all the applied bias will drop across the memory under illumination to trigger the RS. (d) I-V loops for five switching cycles. Initially, the device was in HRS with current levels of nA, which is consistent with the dark current of the bottom photodetector. The current abruptly increases by sweeping voltage to 0.5 V, and the device retained its LRS with a current level of μA for subsequent sweeps. We measured the RS characteristics of 49 devices, and the average ON/OFF ratio of the RS is 1.6×10^3 . The average set and reset voltage are 0.54 V and -0.69 V [see more in Fig. S5 (see the [supplementary material](#))]. (e) Retention and (f) endurance data of the RS memory.

(approximately 0.3 V) was lower than the setting bias (0.5 V), while the memory turned to LRS when the light duration was larger than 1 s ($t = 1$ and 10 s). When illumination duration is short ($= 20$ ms), we observed that the RS state was in the middle process of converting from HRS to LRS, confirming the weak filament formation during the setting process. It should be noted that Fig. 4(a) shows a gradual change of current, rather than an abrupt increase expected for the formation of metallic Ag filaments,^{52,62} which is the result of a large voltage step of 0.05 V used in order to maintain a reasonable measurement speed.

The light intensity also affects the filament formation during the setting process, as shown in Fig. 4(b). The setting condition is the same as before (0.6 V between terminals 1 and 3), while the light intensity was varied from 0 to 1 mW cm^{-2} , and the light illumination duration was fixed at 10 s. We found that the set voltage of the RS memory decreased with an increase in the light intensity, which is expected since the resistance of the photodetector was modified by the illumination condition. A light intensity larger than $10 \mu\text{W cm}^{-2}$ is required to significantly decrease the resistance of the photodetector and to reduce the set voltage of the iconic memory. In fact, the resistance of LRS slightly decreases with the increase in light intensity. At the light intensity of 1 mW/cm^2 , the devices immediately entered the LRS.

Moreover, as shown in Fig. 4(c), the memory resistance depends on the photon energy. Continuous illumination with wavelengths of 627 and 470 nm was applied during the resistance measurement. Due to the bandgap of MPB [Fig. 2(f)], light illumination with a wavelength of 627 nm cannot change the resistance state of the RS memory device. It should be noted that the characteristics of dependence on light illumination conditions are quite different from the previous reports.^{6,14,15} For the transistor-type photomemories, the RS originates from the reversible charge trapping and de-trapping processes, which are modulated by the gating voltage. On the other hand, in the simple device structure demonstrated here, the RS memory and the photodetector are separate components connected in series, leading to excellent tunability and wavelength selectivity. Since the operation mechanism is not hinged on defects, the multilayer artificial iconic memory is more reliable and reproducible.

The temporal response of the current (I_{13}) under 10 mW cm^{-2} illumination at 470 nm is shown in Fig. 4(d). The I_{13} was initially kept in a low conductive state (10^{-9} A) in the dark and abruptly increased to 10^{-6} A upon illumination. At this moment, both of the photodetector and the RS memory were in the LRS. After removing the light, the I_{13} decreased by two orders of magnitude due to the resistance increase in the photodetector, but it is still notably higher than the initial state.

FIG. 4. Photo-programming characteristics of the artificial ionic memory device. (a) I_{12} - V curves measured with a constant bias of 0.6 V between terminals 1 and 3 under light illumination with different durations. The light intensity is 1 mW cm^{-2} with a wavelength of 470 nm. (b) I_{12} - V curves after constant bias between terminals 1 and 3 under different light intensity. (c) Resistance measurement after constant bias between terminals 1 and 3 under the light illumination with different light wavelengths. The light intensity is 1 mW cm^{-2} . (d) Response of the artificial ionic memory device at $V_{13} = 0.5 \text{ V}$ to illumination (470 nm, 10 mW cm^{-2}) of 10 s. In the reset process, a bias of -1 V is applied for 100 ms. (e) Cycles of artificial ionic memory response to light pulses and reset biases. (f) Temporal I_{13} curves under the same illumination condition as (d). The stored current level lasted for more than 5000 s. (g) PL spectra of the artificial ionic memory device taken as fresh and 60 days later. The inset shows the corresponding photos. (h) XRD spectra of the artificial ionic memory device as fresh and after 60 days of storage. (i) Current-time curves of the artificial ionic memory device for the stability characterization. The measurement condition is the same as (d).

The switching ratio of the monolithic artificial ionic memory is approximately three. The higher current of the artificial ionic memory compared to the initial state is owing to the nonvolatile nature of the RS memory, which still retained in the LRS after the light was turned off. As shown in Fig. 4(d), a negative bias pulse of 1 V annihilated the Ag filaments in RS memory, thus resetting the artificial ionic memory to its initial state. This operation loop can be repeated multiple times [Fig. 4(e)], and the programming current I_{13} was able to be retained for more than 5000 s [Fig. 4(f)]. Figure S7 in the [supplementary material](#) outlines the operation sequence and memory states of the artificial ionic memory, and performance comparisons between

our work and other reported artificial ionic memory devices are summarized in Table S1 (see the [supplementary material](#)).

It is well known that hybrid perovskites are unstable in air, which significantly limits their practical application in the solar cells and other optoelectronics.^{63–66} Water is believed to be the major reason for perovskite degradation,⁶⁷ while other factors like device architecture, deposition methods,²⁹ metal contacts,⁶⁸ and light illumination⁶⁹ also play important roles. Compared to the I counterpart, MPB is more stable in the ambient conditions due to its cubic structure and high formation energy,^{70,71} which is critical for achieving reliable artificial ionic memory devices. A recent study found that MPB perovskite

thin films can maintain their structure even after five months aging in an ambient atmosphere with high relative humidity (RH) of 70%.^{70,72} Furthermore, the active layers deposited by the vapor method have better coverage and smooth surfaces compared to those by conventional spin-coating methods, which helps to enhance device reliability.⁴⁶ To check the stability, the artificial ionic memory devices were stored under dark without encapsulation, and the ambient air has a RH level of around 45%. Figure 4(g) shows the photographs of the perovskite/metal multilayer sample as fresh and after 60 days, and no visible color change was observed, which is consistent with previous literatures on MPB perovskite films.^{72,73} The color of Ag electrodes changed from shining silver to dark gray, which is attributed to the oxidation of the Ag surface, while negligible color change of the perovskite layer was observed. Since the PL peak intensity can help to determine the degradation degree, PL measurements were carried out.⁷⁴ After 60 days of ambient storage, the PL intensity of the sample only decreased by less than 30% without any shift of the peak position, indicating that the optical properties were retained. The artificial ionic memory was further characterized by XRD as fresh and after 60 days [Fig. 4(h)]. The cubic phase of the perovskite film basically remains intact, while the extra weak peaks at 26.4° and 37.7° may derive from the appearance of PbBr_2 and MABr due to a small degree of degradation (Fig. S8, see the [supplementary material](#)).⁷²

The impact of ambient storage on the electrical performance of artificial ionic memory was also characterized. Figure S9 (see the [supplementary material](#)) presented the I - V characteristics in the dark and under illumination of the samples measured as fresh and after 60 days. The ON/OFF ratio of the photodetector decreases from 660 to less than 100. The decrease in photocurrent can be attributed to the generation of defects in both the perovskite layers and the interface contacts.⁴³ The shift of the current valley should be due to the chemical reaction between the perovskite and electrode metal.⁷⁵ Nevertheless, the photo-programming characteristics in Fig. 4(i) confirm that the artificial ionic memory device retains its multiple memory states and switching ability after 60 days of ambient storage.

Nowadays, image sensors are widely used in applications of cameras, industry, and defense technologies. To examine the potential of

perovskite photomemories for imaging applications, we integrated an artificial ionic memory array of 7×7 pixels (Fig. S2, see the [supplementary material](#)) with each pixel being embodied by a working artificial ionic memory device. The artificial ionic memory array (49 devices) was exposed to blue light ($\lambda = 470 \text{ nm}$) with a power intensity of 1 mW cm^{-2} for 10 s. As shown in Fig. 5(a), the artificial ionic memory clearly exhibited two current states without any interlaced signal. Furthermore, a pre-patterned “P”-shaped shadow mask was placed on top of the artificial ionic memory array to test its imaging function. The detected current values of each pixel in the artificial ionic memory array were extracted to reconstruct the detected image. As illustrated in Fig. 5(b), the detected current mapping well reproduced the pattern of the light source. The successful implementation of the imaging array without any defect pixel can be attributed to the high uniformity and ambient stability of the perovskite films prepared using the vapor deposition method.

III. CONCLUSIONS

Iconic memory of the human brain entails the coherent collaboration between neural and visual cortex systems.⁷⁶ The photoreceptors in the retina can sense even flashes of light as feeble as three photons in the whole visible spectrum,⁷⁷ while the perovskite photodetector requires a light intensity on the level of $\mu\text{W cm}^{-2}$ for setting to the LRS. Furthermore, multiple parts of the brain are involved in iconic memory, including the cortical areas, ventral stream, and middle occipital gyrus,⁷⁸ which help humans to retain a long-term memory duration. The artificial ionic memory can retain the resistive state for thousands of seconds [Fig. 4(f)], which is largely tunable via judiciously choosing the switching media and the device architecture. The perovskite/metal multilayer structure reported herein is promising for high-density device and network integration.

In summary, we report on the design and fabrication of a novel artificial ionic memory device with an ITO/MPB/Au/MPB/Ag structure. In this simple design, one photodetector and one memory are connected in series, leveraging on the light-responsive and the RS properties of hybrid perovskite layers. Compared with the conventional transistor-type artificial ionic memory, such a multilayer device

FIG. 5. (a) Current statistic values of 49 pieces of artificial ionic memory devices before and after illumination. As shown in here, the artificial ionic memory clearly exhibited two current states without any interlaced signal. (b) A pre-patterned “P”-shaped shadow mask was placed on top of the artificial ionic memory array to test its imaging function. The detected current values of each pixel in the artificial ionic memory array were extracted to reconstruct the detected image. Spatial distribution mapping of a light source image (letter “P”). The light power intensity is 1 mW cm^{-2} with a wavelength of 470 nm. As illustrated in b, the detected current mapping well reproduced the pattern of the light source. The successful implementation of the imaging array without any defect pixel can be attributed to the high uniformity and ambient stability of the perovskite films prepared using the vapor deposition method.

is more straightforward to fabricate without the need of any dielectric gating, which leads to low cost and robust operation. The artificial iconic memory devices presented excellent stability for 60 days in ambient conditions. The imaging capability obtained with the 7×7 artificial iconic memory array further demonstrated the potential of this new perovskite-based device. This design of the architecture enriches the content of artificial sensor memory and creates more possibilities for future AI development.

IV. EXPERIMENTAL METHODS

A. Materials

MABr powder was purchased from Dyesol. All the other chemicals and solvents were purchased from Sigma-Aldrich and are ACS reagent grade.

B. Polycrystalline film growth and device fabrication

A glass substrate was cleaned sequentially with acetone, ethanol, and de-ionized water, and dried under nitrogen gas flow. Afterward, a layer of 60 nm ITO was deposited as transparent conducting oxide (TCO) on the as-prepared glass through a shadow mask by DC-magnetron sputtering in an Ar atmosphere at room temperature and then annealed in air at 250 °C for 30 min. The MPB perovskite thin films were deposited onto the ITO-patterned glass using the dual-sources vapor deposition method.²⁹ As-prepared ITO substrates were loaded into a thermal evaporation chamber (base pressure is below 1×10^{-4} Pa) to deposit lead bromide (PbBr₂) and methylammonium bromide (MABr) simultaneously. The evaporation rate was around 0.4 Å s^{-1} , and the substrates were kept at room temperature. Afterward, a layer of 100 nm Au was deposited through a shadow mask on the perovskite layer with a cross section area of 0.01 mm^2 . Next, a matched square shadow mask was placed on the top of the Au pattern, and another layer of MPB perovskite was deposited by the same method. Last, the artificial iconic memory devices were completed by thermal evaporation of 100 nm Ag through the same shadow mask as top electrodes.

C. Measurements

All the samples were characterized in ambient conditions. Perovskite and PbBr₂ film thicknesses were determined by AFM (Bruker Dimension ICON), and their surfaces were imaged using the same AFM. XRD was carried out on a Bruker D8 ADVANCE diffractometer with Cu K_α ($\lambda = 1.5406 \text{ Å}$) radiation. The morphology and cross-sectional image were examined by FEI Nova Nano 630 scanning electron microscopy (SEM). The current-voltage properties of the devices were measured using a Keithley 4200 Semiconductor Parametric Analyzer and Signotone Micromanipulator S-1160 probe station. The current compliance value is 0.001 A to protect samples from hard breakdown. A calibrated light (470 nm, 627 nm, and white light, from 0 to 100 mW cm^{-2}) light-emitting diode from Metrohm Autolab was used as the light source.

SUPPLEMENTARY MATERIAL

See the [supplementary material](#) for details on the device working mechanism, device photograph, and additional data.

AUTHORS' CONTRIBUTIONS

X.G. and Y.W. contributed equally to this work.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article and its [supplementary material](#).

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