Switchable Perovskite Photovoltaic Sensors for Bioinspired Adaptive Machine Vision

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Machine vision is an indispensable part of today's artificial intelligence. The artificial visual systems used in industrial production and domestic daily life rely significantly on cameras and image-processing components for live monitoring and target identifying. They, however, often suffer from bulky volume, high energy consumption, and more critically, lack of adaptive responsiveness under extreme lighting conditions and thus possible mortal visual disability of flash blinding or nyctalopia for applications such as auto-piloting. Herein, it is demonstrated that perovskite switchable photovoltaic devices are used to effectively construct all-in-one sensory neural network. Arising from the spontaneous and electric field-induced ion-migration effect, the photoresponsivity of the perovskite device can be reconfigured over the wide range of 540–1270%, which not only allows high-fidelity adaptive image sensing of the visual information but also acts as updatable synaptic weight to enable the sensor array for performing machine-learning tasks. With the bioinspired electronic pupil regulation function achieved through adjustable photoresponsivity of the perovskite sensor array, a proof-of-concept adaptive machine vision system with a maximum 263% enhancement of the object recognition accuracy for compact, mobile yet delay-sensitive applications is demonstrated.

1. Introduction

Visual perception endows over 80% of information gathered during human being’s interaction with the surrounding environments,[1,2] which is the most critical sensing system of the mammals and other advanced creatures. Following the nature, cameras and video recorders resembling the retinal sensing function of biological vision organs, as well as artificial neural networks (ANNs) capable of executing image-processing tasks in the way similar to human brains,[3–5] have been extensively studied and widely utilized in modern society for municipal traffic monitoring, industrial manufacturing control, security surveillance, etc. Machine vision with advanced electronic devices and systems has become a vital part of today’s artificial intelligence (AI).[6,7]

Conversion of visual information into digital signals is the first and most pivotal step of machine vision systems. Due to the deliberately predefined internal chemical profile and photoresponsivity of the silicon sensing materials, modern image-sensor devices based on solid-state semiconductor technology can faithfully capture optical images.[8,9] This, nevertheless, is only achievable under proper illumination...
conditions. Although the mechanical aperture that mimics the biological pupil can adjust the amount of light entering the camera, the lack of intrinsic adaptivity to the ambient optical environment and therefore fixed photoresponsivity of the optical sensors limit their capability of producing high-quality images under extreme lighting conditions and greatly influences the accuracy of the following pattern recognition and object detection through machine-learning algorithms. In the meantime, shuffling of the massive and mostly redundant data generated by these image sensors along the sensor–memory–processor signal chains may result in significant latency and energy consumption of the system. The pedantic and power-engulfing nature of these man-made visual systems makes them less competitive in locomotive applications, e.g., pilotless vehicle and humanoid robotics.

Many efforts have been made to emulate the neurobiological functionalities of human eyes, among which materials scientists contribute a lot to achieve individual demonstrations of image sensing and preprocessing for image-contrast enhancement or noise reduction with highly sensitive semiconductor photodetectors,[10–12] as well as pattern recognition through memristive neural network to realize compact and more efficient machine vision for mobile yet delay-sensitive applications.[13–17] A better solution is to redesign the hardware systems to assemble these separate functions into an all-in-one platform,[18,19] wherein the development of switchable photodetectors that can simultaneously sense the visual information in complex environments in a tunable and high-fidelity manner, as well as perform instant and energy-efficient image processing tasks in situ in the sensory array with less or even no delays, is of high demand for user-end AI apparatus.[20] From the materials’ aspect of view, photodetector devices based on organometal halide perovskites distinguish themselves as ideal choices for building such artificial visual systems with better performance and energy efficiency.[21,22] The broadband response of the hybrid crystals to visible lights allows true-color imaging of the examined objects,[23–25] whereas the nonvolatile reconfiguration of materials’ composition and internal potential profile through electric-field-induced ion migration permits switchable photovoltaic responsivity, and thus adaptive imaging with high-fidelity under extreme light conditions.[26–28] In addition, the externally tuned photoresponsivity of the individual perovskite devices may also act as updatable synaptic weight for machine-learning algorithms and turns the image sensor array into an ANN for real-time processing of the visual information.[29]

In this work, we present a ternary cation halide Cs$_{0.05}$FA$_{0.81}$MA$_{0.14}$PbI$_{2.55}$Br$_{0.45}$ (CsFA AMA)-based perovskite switchable visual sensor that exhibits full-visible-spectra photovoltaic behavior and reconfigurable responsivity for adaptive image sensing and in-sensor machine vision. Experimental results demonstrate that imaging of the target object can be achieved in an adaptive manner by the ion-migration-induced switchable photovoltaic characteristics, whereas the tunable photoresponsivity enable the sensor array as perceptron neural network (PNN) for performing simple instant computation tasks. In particular, emulation of the pupil regulation function through a pure optoelectronic means can be used to realize effective image adjustment, which accelerates the recognition of the target object with higher accuracy on the same sensing matrix. The adaptive in-sensor computing showcased in this study provides a promising solution for future machine vision with great overall efficiency and fidelity.

2. Results and Discussion

Human visual system mainly consists of eyes, optic nerves, and cerebral cortex (Figure 1a). Irises and pupil function as camera aperture to regulate the light dose entering the lens and vitreous body, which finally reaches the retina and converts into neural information of brightness and color by the rod and cone photoreceptors, respectively. The coded neural signals transmit along the optic nerve fiber to the cerebral cortex and get decoded to reproduce and recognize the sensed visual information. Under extreme lighting conditions, optical reflections from the target object can be easily obscured with the background darkness or completely concealed by the strong bright stray lights, making it impossible for the retina and cortex to perform effective imaging and target discriminating. Although mechanical pupil and aperture regulation can partially mitigate these issues, it may not fundamentally avoid the occurrence of nyctalopía and instant blindness in either the biological or artificial visual systems. Visual disability is sometimes mortal for vehicle drivers and autopioting AI applications.

Considering the importance of imaging regulation for high-fidelity visual identification, we propose that organic–inorganic hybrid perovskites with reconfigurable ionic and switchable photovoltaic activities are ideal material choices for constructing artificial visual system that combines the adaptive image sensing and object recognition functions (Figure 1b). Layered organometal halide perovskites inherit the specific ABX$_3$ formula of its inorganic counterparts with great flexibility for compositional modifications. The corner-sharing BX$_6$ octahedra consisted of B site lead and X site halides form an extended anionic framework, whereas the A site organic cations occupy the central cavity space. The ionic radii and electronegativities of the cations cause the tilting of the octahedras from the perfect cubic connections and define the lattice symmetry and band structure of the crystal.[30–33] The incorporation of the organic methylammonium (MA$^+$) or formamidinium (FA$^+$) monovalent cations, and their weak interaction with the iodine anions, give rise to full-spectra absorption associated with the band-edge transition of the perovskites in the visible range.[34–37] This is the optical characteristic that makes perovskites promising candidates for photovoltaic and photodetection applications, and renders their sensing capability for full-color imaging. It is noteworthy that the monovalent organic cations and halide anions usually show small activation energy, modest diffusion coefficient and movability in solid-state thin films, in particular when being subjected to external voltage bias or under light illuminations.[38–40] The intrinsic ion-migration phenomena can nonvolatiliey reconfigure the composition gradient and internal potential profile of the perovskites. Change in the materials’ composition may rightfully modulate their energy-band diagram, which in turn influences the optical absorption and carrier-generation characteristics of the photovoltaic devices. In contrast, driven by the external electric field or photovoltaic field, migration of the ionic species to the electrode/perovskite interfaces and their accumulation will build up an
additional electric field $E_{on}$ that alters the potential profile and influences the charge carrier transport and collection dynamics across the photovoltaic matrix. As such, the perovskite may show tuned current output yet unfavored hysteresis for solar cell applications.\[26,41–43\] Nevertheless, the switchable photovoltaic response offers the possibility of reversible and adaptive adjustment of the photocurrents.\[44–46\] Without the necessity of modulating the extent of optical exposure, which is also unlikely to occur in field applications, the contrast of the as-captured images can still be tuned optoelectronically to guarantee a high-fidelity reproduction of the examined object under even nyctalopia or flash blinding conditions (Figure 1c).

Setting the photoresponsivity of each perovskite sensory pixel individually also enables training of the interconnected photovoltaic crossbar array as neural network via matrix–vector product operation. The real-time multiplication and accumulation (MAC) manipulations can be performed by the stateful generation of device photocurrent under short-circuit and illumination conditions, $I_m = R_nP_m$, and summation of the bit line currents according to the Kirchhoff’s law, $I_m = \sum_{n=1}^{N} I_{mn}$, where $R_n$ is photoresponsivity of the $n$th perovskite pixel, $P_m$ denotes the optical power, and $m$ stands for the $m$th bit line. Note that the photoresponsivity of the perovskite-sensing device is a function of the internal ionic state; it can be modulated externally by the applied voltage stimuli as $R_n = aV_n$ and $I_n = aV_nP_n$, where $a$ is a constant and $V_n$ represents the applied voltage. As such, conversion of the optical images directly into the electrical domains of the ANN, or, execution of in-sensor computing on photovoltaic matrix, can unite the computation workloads and the sensory array with small circuit area, short latency, and energy-saving features for the construction of compact and smart-machine vision systems.

With its positive enthalpy (34.8 kJ mol$^{-1}$) of perovskite formation, the most studied modeling material MAPbI$_3$ is intrinsically unstable and may spontaneously decompose to its constituting components.\[25,47\] To obtain a thermodynamically more stable perovskite for device applications, composition modification with both cation and anion substitution has been performed. Partially replacing the iodine with bromine anion may shift the crystal to the edge of stability, with the lower enthalpy (6.7 kJ mol$^{-1}$) of formation offset by small positive entropy. Acceptable mismatch of the ionic radii between that of $\text{I}^-$ and $\text{Br}^-$ helps to avoid significant destabilization of the solid solution. Incorporation of other organic (CH(NH$_2$)$_2$)$^+$, FA$^+$), and inorganic ($\text{Cs}^+$) cations may further enhance the thermodynamic stability of the compound. In this work, we utilize a triple-cation mixed-halide $\text{Cs}_{0.05}\text{FA}_{0.81}\text{MA}_{0.14}\text{PbI}_{2.55}\text{Br}_{0.45}$ perovskite (CsFAMA) to construct switchable photovoltaic-sensing devices.\[48,49\] The successful synthesis of CsFAMA thin film on indium-tin oxide (ITO)-coated glass substrate is confirmed by the X-ray diffraction (XRD) data, as shown in Figure S1, Supporting Information. The diffractive peaks at the $2\theta$ of 13.97º, 19.86º, 24.46º, 28.31º, 31.77º, 34.96º, 40.51º, and 43.16º correspond to the (101), (012), (021), (202), (211), (122), (024), and (131) crystalline planes of the perovskite.\[50\] Scanning electron microscopic images reveal that both the surface and internal regions of the $\approx$500 nm thick perovskite layer show high-quality dense structure without clear pinholes or cracks (Figure S2, Supporting Information).

The CsFAMA film exhibits a broadband absorption covering almost the entire visible spectrum of solar irradiation, and an
intensive luminescence with strong red emission centered at 790 nm (Figure S3 and S4, Supporting Information). A relative narrow optical bandgap of 1.595 eV can be derived from the absorption edge of ≈780 nm, whereas transient measurements indicate that the photon-induced excitation occurs within a short period of ≈1 ns. Together with the low trap density of $9.0 \times 10^{15}$ cm$^{-3}$ (Figure S5, Supporting Information), CsFAMA distinguishes itself as a promising candidate for optoelectronic device applications. Being consistent with the full-visible-spectra absorption behavior, the Au/CsFAMA/ITO device shows sensitive photocurrent responsiveness to the red (655 nm), green (532 nm), and blue (405 nm) illuminations (Figure 2a). As the optical power increases from 0.5 to 256 mW cm$^{-2}$, an excellent linear and 256-level responses of the photocurrent (read at 0.1 V) can be observed for all RGB (red, green, and blue) stimulations (Figure 2b). All the states can be differentiated clearly. As such, a single pixel incorporating three CsFAMA photovoltaic devices for individual RGB sensing is able to detect 16 million combinations of true-color imaging. The biased voltage is applied to the Au electrodes throughout this work, whereas the ITO substrates are always grounded.

Hysteresis in the direct-current (DC) photocurrent–voltage characteristics is recorded as an indicator of the potential ion migration in CsFAMA films (Figure 2c). When scanning from −0.5 to +0.5 V with a step speed of 0.1 V s$^{-1}$, the device current minimum appears at the biased voltage of ≈0 V with the white illumination of 40 mW cm$^{-2}$. For photovoltaic materials, the exposure to optical illumination results in direct generation of the bounded excitons that eventually dissociate into free electrons and holes. Driven by the biased voltages, these charge carriers will migrate to the cathode and anode, respectively, and produce a photovoltaic field $E_{PV}$ with its polarity opposite to that of the external electric field $E_B$. During the DC scanning measurements, the measured device current is in fact a competing result of these fields as

$$I = \frac{E_B - E_{PV}}{R_{PV}}$$

where $R_{PV}$ is the resistance of the photovoltaic material. Thus, the scanning voltage at which the current minimum appears corresponds to the strength of the photovoltaic field $E_{PV}$. In case of the present organometal mixed-halide perovskite CsFAMA, the scanning voltage may also lead to the migration of ionic species to the electrodes under the biased voltage (Figure S6, Supporting Information). Accumulation of the ionic species at the electrode/perovskite interfaces will build up an additional electric field $E_{ion}$ with reverse polarity to $E_B$ and alters the potential profile inside the photovoltaic matrix. The change in the composition gradient across the perovskite will also modulate its responsivity to the optical illumination, e.g., light absorption, exciton generation and dissociation, charge carrier transport capability, and exhibit

**Figure 2.** a) Photocurrent responses of the Au/CsFAMA/ITO device read at 0.1 V, under red (655 nm), green (532 nm), and blue (405 nm) illuminations with different optical powers for 5 s. b) 256-level linear photocurrent responses of the device current under blue illumination in the optical power range of 1 to 256 mW cm$^{-2}$. The ramping step widths in (b) and inset are 1 and 16 mW cm$^{-2}$, accordingly. c) Photovoltaic characteristics of the device obtained under white illumination of 40 mW cm$^{-2}$ and different DC voltage scanning speeds. d) Photocurrent responses of the CsFAMA device recorded under −0.02 V constant voltage stressing and white illumination of increasing optical powers.
tuned photovoltaic characteristics. During the backward scanning from +0.5 V to −0.5 V, the migrated ions cannot keep up with the changing electric field, and the nonequilibrium state device current turns to

\[
I = \frac{E_B - E_{PV} - E_{ion}}{R_{PV}} = \frac{E_B - (E_{PV} + E_{ion})}{R_{PV}} = \frac{E_B - E'_{PV}}{R_{PV}} \quad (2)
\]

where \(E'_{PV}\) and \(R_{PV}\) represent the new photovoltaic field and device resistance controlled by the internal ionic state of the CsFAMA layer. Clearly, this will lead to a shift in the current minimum in the I−V characteristics, wherein \(E'_{PV}\) equals to the sum of \(E_{PV}\) and \(E_{ion}\) and accounts for the dynamic hysteresis shown in Figure 2c.[28,51,52] As the speed of the voltage scanning operation slows down to 0.005 V s\(^{-1}\), the mobile ionic species may gain sufficient opportunities to migrate back to their equilibrium states, resulting in a much-reduced hysteretic current–voltage curve.[53,54]

The electrical hysteresis is generally considered disadvantageous for solar energy conversion,[55–57] whereas for smart imaging applications the ion-migration-induced photocurrent regulation may provide an effective approach of self-adaptation under extreme lighting conditions.

Under constant voltage scanning speed, the electrical hysteresis recorded with optical illumination (white light, 40 mW cm\(^{-2}\)) is smaller than that obtained in dark environment (Figure S7, Supporting Information), suggesting that the light exposure can promote the speed of ion migration and make them reach the equilibrium state faster. When a negatively biased electric field (−0.02 V) which is much smaller than the photovoltaic field \(E_{PV}\) is applied onto the CsFAMA device, a positive device photocurrent can be observed as shown in Figure 2d. The photovoltaic field may also drive the cations of the perovskite to migrate toward the ITO cathodic electrode, whereas the anionic species will move to the Au anodic electrode, respectively (Figure S8, Supporting Information). The additional field \(E_{ion}\) built up by the accumulated ions shows reverse polarity to that of the photovoltaic field, which decreases the overall strength of the net electric field across the perovskite layer gradually and consequently lowers the device photocurrent outputs. Increasing the optical illumination power will promote the migration of ions to a greater extent, which in turn results in a faster spontaneous relaxation of the photoresponses (Figure S9, Supporting Information). A maximum 540% relaxation of the device current and photoresponsivity can be deduced from Figure 2d. On the other hand, the application of positive biased electric field that exceeds the photovoltaic field will give rise to positive current that increases with time (Figure S10, Supporting Information). These attenuation characteristics are similar to the short-term depression (STD) and short-term potentiation (STP) of biological synapses. Removing the electrical and optical stimuli will allow the perovskite system to relax to its initial state, wherein the cyclic measurements suggest that the self-adaptive photovoltaic sensing characteristic can be reproduced with promising accuracy and reliability (Figure S11, Supporting Information).

Beyond the spontaneous relaxation of the photoresponses, voltage-induced ion migration can further facilitate the active regulation of CsFAMA device performances via giant switchable photovoltaic activities. As shown in Figure S12, Supporting Information, the continuous application of 1 V voltage to the perovskite photovoltaic sensor can lead to the migration of anions toward the Au electrode and cations to the ITO electrode, which forms an additional negative field \(E_{ion}\) across the CsFAMA layer. This ionic field will boost the negative photovoltaic field \(E_{PV}\) produced upon optical illumination and gives rise to a larger nominal \(E_{PV}\). Increasing the voltage stressing time from 10 to 40 s will cause more ions to migrate inside the perovskite film, resulting in larger \(E_{ion}\) and gradually increased \(E_{PV}\) as recorded in Figure 3a. The long sampling time used herein is to ascertain the occurrence of noticeable switchable photovoltaic phenomena and can be optimized (e.g., with higher voltages) and shortened to speed up the hardware system during practical operation. According to the following equation

\[
I = \frac{E_B - (E_{PV} + E_{ion})}{R_{PV}} = \frac{E_B - E'_{PV}}{R_{PV}} \quad (3)
\]

the photoresponsivity \(r\) (or photocurrent) of the CsFAMA photovoltaic sensory device decreases from 0.23 to 0.018 mA V\(^{-1}\) (≈1270%) with the increase in the voltage stressing time from 0 to 40 s (Figure 3b), wherein \(P\) stands for the incident light intensity. When the polarity of the stressing voltage is reversed, a decreased nominal \(E_{PV}\) and increased device photoresponsivity can be observed (Figure S13, Supporting Information). Long-term depression (LTD) or long-term potentiation (LTP) can also be achieved after constant voltage stressing (Figure 3c,d). Both the spontaneous relaxation and active regulation of the CsFAMA photoresponsivity are of great importance to achieve self-adaptation of the optoelectronic sensory device for smart image sensing. For instance, deliberate down-tuning of the photocurrent output can generate high-fidelity image with enhanced contrast of the targeted object against the dazzling backgrounds, offering an electrical analog of the pupillar mechanical regulating functionality. In field applications where it is less possible to change the illumination intensity, the occurrence of nyctalopia or flash blinding can be effectively avoided through self-adaptive optoelectronic modulations.

To confirm the occurrence of ion migration accounting for the switchable photovoltaic characteristics observed in CsFAMA devices, photo-induced force microscopic (PiFM) technique was used to visualize the 2D optical absorption signal evolution of the ionic species inside the perovskite film in-situ. In general, laser illumination that fits the sample’s absorption band will cause polarization of the examined molecules, which can be measured through dipole–dipole interaction with the atomic force microscope (AFM) tip via mechanical force detection.[58] The near-field excitation and detection thus allow us to monitor the composition-related absorption and variation of the ionic species distribution in real-time domain.

In comparison to that of the PbI\(_2\) and CsPbI\(_3\) samples, the UV-visible absorption spectrum of the CsFAMA film demonstrates clear extension into the red region of 600–780 nm, which can be attributed to the presence of organic FA\(^+\)/MA\(^+\) cations and their interaction with the anionic PbI\(_{3.55}\)Br\(_{0.45}\) framework.[59,60] Therefore, we adopted the Nano Vis mode measurement of the PiFM microscope to collect visible range absorption-mapping data for a better understanding of the field-induced ion-migration behavior. The granular topology of the as-synthesized CsFAMA film (Figure S14, Supporting Information) obtained by AFM

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microscope is similar to the SEM patterns shown in Figure S2, Supporting Information. As shown in Figure 4a–f, the perovskite film exhibits absorption to the 650 nm visible illumination over majority of the sample area, suggesting the uniform coverage of the sample surface with the organic cations. When a −1 V voltage stimulus is applied through Pt-coated AFM tip onto the perovskite layer, the intensity of the PiFM signal increases significantly, indicating that the organic cations are attracted by the external electric field from the interior section of the CsFAMA film to the surface area (Figure 4g). As the stressing voltages decreased from −1 to 0 V in a 0.2 V step, the electric field that holds the positively charged ions gets attenuated gradually and becomes less efficient to maintain the surface cationic species. Consequently, a part of these ions drift back into the deep region of the CsFAMA layer under concentration gradient, whereas the absorption associated with the smaller amount of FA<sup>+</sup> and/or MA<sup>+</sup> cations presenting in the surface region decrease in both the maximum signal intensity and absorption areas. When the polarity of the stressing voltages is reversed, the organic cations are driven away from the perovskite surface area by the downward-pointing electric field, which in turn annihilates the absorption intensity significantly (Figure 4h–n). Figure 4n well repeats the

Figure 3. Photovoltaic characteristics and photoresponsivities of the CsFAMA device obtained under white illumination of 40 mW cm<sup>−2</sup>, after being subjected to constant voltage stressing at a,b) 1 V for different periods of time, respectively. The current responses in (a) are not drawn to scale for a clearer illustration of the F<sub>PV</sub> evolution while the photoresponsivities in (b) are read at 0.32 V. c,d) Regulations of the device photoresponsivity by constant voltage stressing, corresponding to LTD and LTP behaviors of biological synapses, respectively. e) Current–voltage curves of the CsFAMA device under white illumination with different optical intensities. f) Plot of device conductance and photocurrent versus white illumination intensity with data derived from (e). The photocurrent in (f) is read at 0.2 V from the I–V curves of (e).
PiFM absorption pattern of Figure 4a, suggesting that the electric field-induced ion migration in CsFAMA perovskite film is almost fully reversible. Although the iodine and bromine anions exhibit lower diffusion barrier of 0.17 eV than that of the ammonium-based cations (0.3 eV),[61] and thus appear easier to migrate under the stimulation of external electric field or optical excitations, the lack of recordable optical absorption makes their distribution unable to be visualized during PiFM observation. Nevertheless, the observed changes in the PiFM patterns and their correlation with the organic FA$^+$/MA$^-$ cation manipulation by voltage stressing between $\pm$1 V, confidently evidence the occurrence of ion migration in the CsFAMA film. Over the past few years, great efforts have been made to solve the stability issue of the organo-metal halide perovskite materials that are arising from the ion-migration phenomena. Upon optimizing the hydrids' composition or taking proper encapsulation actions to isolate the atmospheric moisture and oxygen species,[62–64] or using the additional electrical field to control the reversibility of ion-migration process,[65–68] fully reversible electrical and optoelectrical responses have been reliably demonstrated.[69,70] We believe that the giant switchable photovoltaic characteristics and reconfigurable photo-responsivity of CsFAMA under the external electric fields can offer promising solution to achieve the proposed adaptive imaging and in-sensor neuromorphic pattern recognition tasks.

Conventional artificial visual system relies on the complementary metal-oxide semiconductor (CMOS)-based image sensor and field-programmable gate array (FPGA) to convert the optical signal into voltage spikes. An additional neural network is required to execute convolution for target recognition, which is recently intensively performed with memristor crossbar arrays. Machine vision involving both the self-adaptive image sensing and in-sensor computing may enable smart and faithful capturing of the visual information from the environment, as well as offer in situ efficient image-processing capability by avoiding the massive shuttling of abundant data between the sensor and computing units.[20,29] This is critically important for user-end applications wherein the fast responding and decision-making is vital, e.g., instant detection and dodging of on-road obstacle during vehicle autopiloting. MAC is the core module of convolution for target recognition in ANNs. Crossbar architecture and parallel operation of the interconnected sensors may allow the natural summation of the device currents following Kirchoff’s law, whereas multiplication can be realized with Ohm’s law of $I = V \cdot \frac{1}{R}$ with V donating the device’s conductance. In the present CsFAMA devices, the current–voltage characteristics show strong dependence on optical illumination (Figure 3e). Replotting the device conductance and photocurrent against the irradiation intensity $P$ gives linear relationships of $G = a \cdot P + G_0$ and $I = a \cdot V \cdot P + I_0 = R \cdot P + I_0$ (or $I - I_0 = a \cdot V \cdot P = R \cdot P$) that satisfy the multiplication requirements of neural networks, where $a$ is a prefactor constant, $G_0$ and $I_0$ are the device conductance and current under dark condition, and $R = a \cdot V$ mathematically equals to the photoresponsivity of the system (Figure 3f). It is noteworthy that the photoresponsivity of the CsFAMA devices is a functional of the perovskite’s internal ionic state and can be controlled by the biased voltage $V$ nonvolatily as demonstrated previously, allowing itself as linearly updatable synaptic weights to optoelectronically train the perovskite photovoltaic sensory array for target-recognition tasks without additional neural network hardwares.

Simulation of PNN with the CsFAMA photovoltaic sensory devices was performed under the TensorFlow framework for machine vision applications, which uses the optical illumination intensity, photoresponsivity and photocurrent as the input, variable weight and output of the optoelectronic synapses, respectively (Figure S15, Supporting Information). For demonstration, images of human faces, aircrafts, automobile vehicles, and flying birds are obtained from the CIFAR dataset of the Keras library, respectively (Figure S15, Supporting Information). Each class of these patterns contains 50 samples, which are converted into $32 \times 32$ pixel jpg sub-pictures in red, green, and blue primary colors. The strength of individual pixel, reflecting the intensity of light reflected from the examined objects, can be directly represented by the power of illumination that approaches the
image sensor during photographing. Therefore, light intensity can be used as input signal of the neural network and intrinsically connects the sensing and computing capability of the present perovskite devices. Accordingly, the PNN network is designed with a $32 \times 32 \times 3$ Flatten input layer, a $60 \times 52$ perceptron layer that executes the MAC operation with the perovskite devices, and a Dense output layers showing $n$ possibilities according to the numbers of the potential patterns. Supervised learning using the back-propagation algorithm on these images shows that ideal accuracy of 100% can be achieved with single-layer PNN for human face recognition (Figure S15, Supporting Information), which, nevertheless, is not the real case in field applications considering the differences in lighting conditions. For instance, over-exposure under dazzling environment will result in the formation of featureless white images that shows none of the target details and may lead to misrecognition by the ANNs.

From the biological perspective, the unconditioned reflex of pupil contraction can help to protect the retinas of human eyes from being damaged by strong lights, while still allows us to see clearly. It is an instinctual behavior of mammals and does not require postnatal learning.[72] The spontaneous relaxation of photocurrent via photovoltaic field-induced ion migration in the CsFAMA device well resembles the self-adaptation behavior of image sensing in biological visual systems. As shown in Figure 5a, the over-exposed image can be prefiltered to remove the background noise and consequently processed with the same perovskite photovoltaic sensor array based multilayer PNN. With the relaxation dynamics extracted from curve-fitting of the device responsivity by Boltzmann function as shown in Figure 5b, high-fidelity reproduction of the captured images of aircraft, automobile vehicle, and flying bird can be made possible in a stepwise manner by the sensing–filtering neurons (Figure 5c and Movie S1–S4, Supporting Information). This leads to correction

![Figure 5](image-url)
of the false recognition of the targeted object in the images. For example, the untreated over-exposed image of an aircraft being subjected to the same PNN will be mistaken as a flying bird, with the pattern features of these two objects being similar. The recognition rate has been reduced to 88%, 62% and 38% for all the images of vehicles, aircrafts, and flying birds, respectively (Figure 5d). With self-adaptive imaging, although the identification is wrong at the very beginning, the recognition rate rises rapidly as the adaption period increases, and the PNN network is capable to recognize the aircraft inside the image correctly in 0.9 s (Figure 5e). For vehicle and flying bird, the correct recognition takes a little longer time, but both can be completed in no more than 3.3 s of adaption time. Accurate recognition for all the images can be completed within 4.2 s.

To accelerate the speed of object recognition from the blurry images, active regulation can be used to replace the spontaneous relaxation, wherein the biased electric field can set the perovskite sensing layer to the desired ionic state immediately with expected relaxation, wherein the biased electric field adjustable photoresponsivity for adaptive image formation is wrong at the very beginning, the recognition rate enhanced accuracy. Combining the complete true-color sensing and object-recognition functions of modern visual surveillance system within the all-in-one sensor neural network, in particular, the field adjustable photoresponsivity for adaptive image formation, the perovskite photovoltaic sensory array exhibits great potential in compact and smart machine vision for future vehicle autopiloting and humanoid robot applications.

3. Conclusion

In summary, we demonstrated a proof-of-concept adaptive machine vision system based on CsFAMA perovskite sensor arrays. Associated with the ion-migration procedure of the organometal mixed halide perovskite, the sensory devices exhibit full-visible-spectra photovoltaic characteristic and switchable photoresponsivity over 540–1270 nm range that allow the constructing of a full-function PNN capable of executing high-fidelity imaging and in-sensor computing with a maximum 263% enhanced accuracy. Combining the complete true-color sensing and object-recognition functions of modern visual surveillance system within the all-in-one sensor neural network, in particular, the field adjustable photoresponsivity for adaptive image formation, the perovskite photovoltaic sensory array exhibits great potential in compact and smart machine vision for future vehicle autopiloting and humanoid robot applications.

4. Experimental Section

Synthesis and Characterization: HC(NH3)2I (FAI) and PbI3 were dissolved in a mixed solvent of anhydrous N,N-dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) (νν = 4:1) to give precursor I solution with 1.211 M FAI and 1.275 M PbI2. CH3NH3Br (MABr) and PbBr2 were dissolved in the same mixed solvent to give precursor II solution containing 1.425 M MABr and 1.500 M PbBr2. CsI was dissolved in DMSO to give 0.750 M precursor III solution. Then 440 μL (I), 66 μL (II), and 44 μL (III) solutions were mixed and stirred at room temperature for 12 h to give the perovskite precursor solution. ITO-coated glass substrates were cleaned by sequential ultrasonic treatment in detergent, deionized water, anhydrous ethanol, acetone, and isopropyl alcohol, each for 20 min, and then dried with nitrogen stream. Afterward, the substrates were treated with UV-ozone for 20 min in plasma cleaner and placed in a nitrogen-filled glove box for perovskite deposition. Perovskite precursor solution (12 μL) was spin-coated onto ITO substrate under 1000 rpm for 10 s and 4000 rpm for 60 s. At 30 s before the end of spin coating, 68 μL of anisole was jetted onto the spinning sample. The as-formed layer on ITO substrate was then annealed at 110 °C for 20 min to give the final CsFAMA film. All the materials used in this work are commercially available.

The crystalline structure of the as-synthesized perovskite film was investigated by XRD technique (Bruker AXS, D8 Discover) using Cu Kα radiation. The top and cross-sectional images of the perovskite film were recorded on Hitachi SU8010 field-emission scanning electron microscope (FE-SEM). The UV–visible absorption spectral measurements were performed on a Shimadzu UV-2450 spectrophotometer. The steady-state photoluminescence (PL) spectrum of the sample was measured by fluorescence spectrometer of Edinburgh instrument company (FSS). The time-resolved photoluminescence (TRPL) spectroscopy spectrum was recorded with Fls-800 spectrometers.
Artificial neurons were composed of a $60 \times 32$ (which must be larger than the number of neurons in the input layer) matrix. In this study, the output layers have three nodes for both the human face and aircraft/vehicle/bird recognition tests. All the images come from the CIFAR dataset of the Keras package as the training and recognition samples. During training and recognition, the image size is first converted to $32 \times 32$ pixels, and then the RGB weights of each pixel are extracted to result in a $32 \times 32 \times 3$ array. The as-obtained datasets are then projected onto the Flatten input layer of SLP or the filtering layer of the MLP network. Self-adaption of the over-exposed images is mathematically conducted according to the spontaneous relaxation dynamics of the CsFAMA device, as shown in Figure 5b, with the fitted formula

$$y = x \left(1 + \frac{100}{1 + e^{t}}\right)$$

where $y$ and $x$ represent the RGB weight of the pixel before and after autonomous adjustment and $t$ is the adaption period. The adjusted weights are used as the input for the perceptron layer. The network of the perceptron layer generates three probability numbers through MAC of the neurons with photoresponsivity as linearly updatable synaptic weights. Adaption used as the input for the perceptron layer. The network of the perceptron layer was composed of a $60 \times 32$ matrix. In this study, the output layer classified the image patterns by comparing the value of the probability numbers with the known image tags. For SLP, the self-adaptation step is omitted and the neural network recognition image pattern upon MAC operation directly.

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

adaptive image sensing, in-sensor computing, machine vision, perovskite photovoltaics, visual sensors

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