Color-Recognizing Si-Based Photonic Synapse for Artificial Visual System

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1. Introduction

In the process of exploring the unknown world, the human visual system plays an important role. It is reported that nearly 80% of the information humans receive from the outside world is obtained through vision, and about half of the human cerebral cortex is involved in the analysis of the visual world.[1] With the continuous expansion of the exploration field, powerful artificial visual systems similar to the human visual system are highly demanded for new intelligent systems to execute various tasks such as signal detecting, processing, and identification in extreme environments. However, so far, the traditional machine and a robot vision system composed of a detector and a computer are not comparable with the human vision system composed of human eyes and vision centers. The existing detectors are usually passive and unadjustable,[2] making it difficult to perform effective signal detection in extreme environments. In addition, it is well known that it is difficult for traditional computers based on the Von Neumann architecture to perform complex computing tasks in an energy-efficient manner due to the limitation of the physical separation of processing and memory units.[3] Moreover, it is also difficult for software to simulate highly complex neural behaviors in the brain during information processing.[4] To break these blocks, neuromorphic chips based on synapses have been proposed to simulate the data processing method of the brain at the hardware level, achieving efficient processing of complex data. So far, various electronic devices have been extensively explored to emulate synaptic dynamics (synaptic plasticity) in the nervous system.[5] These synapses are typical electrically triggered devices, and when used in the artificial vision system, they are unable to respond to the optical signals directly, still requiring additional photon–electron conversion devices for the vision system application. Therefore, an optical sensing module is demanded to convert the optical signals into electrical signals for subsequent processing.[6]

Obviously, synapses with optical sensing functions are more suitable for artificial vision systems and can realize energy-efficient pattern recognition. Recently, a photonic synapse has been proposed that is triggered by light and features high-speed and broad-bandwidth computing.[7] The nature of the direct light...
response combined with the neuromorphic computing ability makes it promising for efficient artificial vision systems. So far, the synaptic functions of the photonic synapses have been demonstrated based on various materials such as perovskite quantum dots,[8] Si nanocrystals,[9] carbon nanotubes,[10] and 2D materials,[11] as well as other material systems.[12] In addition to synaptic functions themselves, the photonic synapses have also been explored for artificial vision systems, and they have shown unique advantages for light triggering. Gao et al. reported a simple heterojunction photonic synapse that could imitate the mechanical aperture device to adaptive optical perception, enabling neuromorphic function and showing human visual memory behavior.[12] Subsequently, Zhao et al. also reported a photonic synapse that achieved similar functions based on different materials.[13] However, these photonic synapses could not distinguish different colors in a single device unit due to the limitations of their functional layers, which are not sensitive to the wavelength of stimulating light, failing to mimic the colored pattern recognition function of the human visual system.

Here, a Si-based photonic synapse with an indium tin oxide (ITO)/amorphous silicon (a-Si)/p+-Si structure is proposed and demonstrated. Through the light adjustment of dangling bond defects inside the a-Si film, the photonic synapse exhibits volatile and nonvolatile dual photoconductivity (PC) behaviors in a single device stimulated by 635 and 450 nm light, respectively. This unique dual PC endows the synapse with the two types of synaptic plasticity depending on the stimulation wavelength, allowing the device not only to have various synaptic functions but also to have learning experience and associative learning behavior. More importantly, based on the dual PC behaviors, our photonic synapse can distinguish two colors (red and blue) in a single device, realizing the detection of light information, extraction of grayscale and color information, colored pattern recognition, and memory functions. Moreover, by applying a voltage below 1 V to the device, synaptic plasticity could be flexibly adjusted, endowing the device with the ability to mimic the environmental adaptation and selective memory functions of the human visual system. The photonic synapse is simple in structure, and fully compatible with the existing Si-complementary metal oxide semiconductor (CMOS) technology, showing vast potential for application in the neuromorphic computing and advanced robot visual systems.

2. Results and Discussion

2.1. Device Structure and Volatile/Nonvolatile PC

A structural schematic of our device is shown in Figure 1a. As shown, the device is composed of an a-Si film as the functional layer sandwiched by a top electrode (an ITO film with a diameter of ≈300 μm) and a bottom electrode (the p+-Si substrate), forming a vertical structure of ITO/a-Si/p+-Si. The top ITO electrode also works as an optical window for light to interact with the a-Si functional layer. A voltage of ≈0.06 V is applied to monitor the photoresponse of the device. Figure 1b shows a cross-section scanning electron microscopy (SEM) image of the device. The thicknesses of the a-Si layer and the ITO layer are both ≈200 nm. Figure 1c shows a typical Raman spectrum of the a-Si thin film. Four peaks could be obtained by Gaussian fitting, located at 143, 296, 404, and 476 cm⁻¹, corresponding to TA, TO, LO, and LA modes of the a-Si film, respectively.[13] Figure 1d,e shows the current evolution process of the device under the 635 nm light illumination at an intensity of 189 mW cm⁻² and the 450 nm light at an intensity of 110 mW cm⁻², respectively. An obvious current increase (photocurrent) and a subsequent decay occur when the light is turned on and off, respectively. In detail, current changes (ΔI) can be observed under continuous illumination (20 s), which are 18.54 nA for the 635 nm light and 11.49 nA for the 450 nm light, respectively. When the light is turned off, a significant photocurrent decay can be observed, as shown in Figure 1d,e.

Interestingly, there is a significant difference between the two persistent PCs induced by the 635 and the 450 nm light. For the red light at 635 nm, as soon as the light is turned off, the photocurrent experiences attenuation, then rapidly goes back to the initial state in less than 10 s, showing the volatile PC (Figure 1d), while for the blue light at 450 nm, after removing the light, the photocurrent experiences a relatively slow decay and does not return to the initial state in up to 30 s, showing the nonvolatile PC (Figure 1e). In summary, the red light generates more photocarriers than the blue light, while the blue light illumination induces nonvolatile PC (persistent PC).

The difference between the volatile and nonvolatile PCs can be further confirmed by fitting the photocurrent curves using the Kohlrausch stretched-exponential function[14]

\[ I = I_0 + \Delta I \cdot \exp\left(-\frac{t}{\tau}\right)^\gamma \]  

where \( I_0 \) represents the background current without light stimulation, and \( \tau \) and \( \gamma \) denote the relaxation time constant and the stretching exponent, respectively. It is reported that a stretched-exponential function could well describe the relaxation of the electron in disordered materials.[14] By fitting the experimental curves in Figure 1d,e, \( \tau \) is determined to be 18.29 s for the blue light and 1.88 s for the red light, respectively, and \( \gamma \) is 0.49 for the blue light and 0.67 for the red light, respectively (Figure 1f). The fitting results show that the relaxation time constant \( \tau \) for the blue light is about ten times larger than that for the red light, confirming a significant difference between the volatile and nonvolatile PCs induced by the red and blue light, respectively.

Shorter light pulses with 100 ms width have also been used to study the photoresponse of the photonic synapse, showing a similar behavior (Figure S1, Supporting Information), which also indicates that the operating speed of our device can reach to the level of milliseconds. The photoelectric conversion efficiency could be improved by enhancing the light absorption in the a-Si film.[15]

2.2. Mechanism of Volatile/Nonvolatile PC

Figure 1g,h demonstrates the photocurrent response of the device under different laser intensities. It can be seen that for the 635 nm light, the photocurrent response of the device increases significantly with increasing the light intensity. After the light is turned off, for all the light intensities, the current quickly returns to the same initial state, which is in the volatile state. For the 450 nm light, however, the situation is quite
different. As shown in Figure 1h, with increasing light intensity, not only does the photocurrent response of the device increase significantly when the light is turned on, but also the corresponding persistent PC phenomenon becomes more and more obvious when the light is off. More results with different laser conditions are shown in Figure S2, Supporting Information. Figure 1i plots the variations of the photocurrent response ($\Delta I$) and relaxation time constant ($\tau$) as a function of laser intensity at 635 and 450 nm, respectively. As shown in the figure, for 450 and 635 nm light, the slopes of the curves for the laser-intensity-dependent photocurrent $\Delta I$ are almost the same ($\approx 0.05$). This result indicates that in this photonic synapse, the photocurrent generation is independent of the light wavelength. In comparison, the light-intensity-dependent $\tau$ curves are completely different for different wavelengths. This result shows that after the light is turned off, the current evolution in the device is related to the wavelength of the stimulating light, indicating different current relaxation mechanisms.

It is believed that persistent PC is caused by the capture/decapture of carriers at the interface of heterojunctions,[9] the defects of the material,[10] or the ionized oxygen vacancies.[11] For Si material, dangling bonds are generally believed to be the origin of the persistent PC.[7] It is well known that there exists a significant Staebler–Wronski effect in a-Si film, where a large number of Si dangling bonds are generated inside the a-Si film upon light illumination, resulting in the formation of more dangling-bond defect states in the forbidden band.[16] This dangling-bond defect state is a deep energy level due to the asymmetry of the conduction band and the tail of the valence band.[17] Such formation of the deep energy level could have a significant impact on the photocurrent response of the device. The formation of dangling bonds is closely related to the breaks of Si–Si weak bonds induced by light, and an activation energy ($E_a$) of $\approx 0.7$ eV is required to break the weak Si–Si bond inside the a-Si film.[18] In this work, the 450 nm (2.75 eV) blue light has enough energy to break the weak Si–Si bonds after overcoming the bandgap energy ($E_g$) of $\approx 1.6$ eV. However, the 635 nm (1.95 eV) red light is hardly able to break the weak Si–Si bonds after overcoming the $E_g$ of $\approx 1.6$ eV. Accordingly, a change in the excitation light energy ($h\nu$) could cause a significant change in the photocurrent response and photocurrent decay.

Figure 1. a–c) Structure schematic and photocurrent response characterization. a) 3D structure schematic, b) cross-section SEM image of ITO/a-Si/ $p^{++}$-Si device, and c) Raman spectroscopy of the a-Si layer. d–e) The photocurrent response of the device under laser illumination at (d) 635 nm and (e) 450 nm as well as the fitting curves of the persistent PC extracted from (d) and (e). g,h) The effect of laser intensity on the photocurrent stimulated at (g) 635 nm and (h) 450 nm. i) Photocurrent $\Delta I$ and the decay time $\tau$ of the device as a function of laser intensity.
Based on the previous discussion, we proposed a possible mechanism for the wavelength-dependent volatile/nonvolatile PC, as shown in Figure 2. There are a lot of intrinsic dangling bond defects (shallow-level traps) in the a-Si film of the device (inset of Figure 2a). As shown in Figure 2b, when the device is stimulated by the 635 nm light, as $h\nu < (E_g + E_a)$, the induced photogenerated carriers inside the a-Si film are captured by the intrinsic dangling-bond defect levels ($E_{D0}$), as shown in Figure 2b (1–2). After removing the laser, the traps could quickly release the captured electrons (Figure 2b (3–4)), and the conductivity of the device quickly returns to the initial state, leading to a volatile PC (Figure 2a). When the device is stimulated by the 450 nm light, as $h\nu > (E_g + E_a)$, the photogenerated carriers could induce the breaking of the weak Si–Si bonds to form new dangling-bond defects, creating new defect energy levels ($E_{D1}$, deep-level traps) in the bandgap, as shown in Figure 2c. During this process, both $E_{D0}$ and $E_{D1}$ take part in the capture and release of the photogenerated carriers, as shown in Figure 2d. After removing the laser, the deep traps slowly release the captured electrons, resulting in a nonvolatile PC, as shown in Figure 2c.

2.3. Light-Stimulated Dual Synaptic Plasticity

The persistent PC behavior plays a very important role in the realization of synaptic functions. Based on the unique volatile/nonvolatile PC behaviors discussed earlier, a light-triggered photonic synapse can be built.

2.3.1. Paired Pulse Facilitation (PPF)

PPF refers to the phenomenon that a second presynaptic spike induces a larger postsynaptic current than the first presynaptic spike in the synapse under two consecutive spike stimuli, which plays an important role in the recognition of visual and auditory signals by a biological nervous system.

Figure 3a shows the photocurrent response of our device to a pair of light pulse stimuli. It can be clearly observed that when a pair of 450 nm light pulses are applied to the device, a larger photocurrent is evoked by the second one. For a pair of 635 nm light pulses, a similar phenomenon can also be observed, as shown in Figure 3b. Here, the light pulse acts as a presynaptic spike and the photocurrent acts as the postsynaptic current. This photocurrent behavior is very similar to the PPF of a biological synapse, implying that our device could serve as a light-triggered photonic synapse. Here, the PPF gain can be increased by appropriately increasing the reading voltage (Figure S3, Supporting Information).

The PPF can be quantitatively described as:

$$\text{PPF index} = \frac{A_2}{A_1} \times 100\%$$

in which $A_1$ and $A_2$ denote the current changes induced by the first light pulse and the second light pulse, respectively. Using the PPF index, we can make a comparison between the PPF behaviors of the photonic synapse under light stimulation at 635 and 450 nm. Figure 3c plots the PPF index as a function
of the pulse interval $\Delta t$. It shows that the PPF index gradually decreases with the pulse interval $\Delta t$ increasing, implying that the photonic synapse could well mimic biological synapses with the PPF function. In some biological synapses, PPF is observed when the stimuli are delivered with intervals from tens of milliseconds to seconds.\cite{22} It can be seen from Figure 3c that PPF can be observed for when the stimuli delivered are at intervals of $0.1-3$ s. The timescales of the stimulus interval are similar to those of biological synapses, which has also been observed in other photonic synapses.\cite{10a,b}

The PPF index as a function of the pulse intervals can be fitted by\cite{21}

\[ Y = 1 + K_1 \times \exp(-\Delta t/\tau_1) + K_2 \times \exp(-\Delta t/\tau_2) \]  \hspace{1cm} (3)

where both $K_1$ and $K_2$ are the initial facilitation magnitude, and both $\tau_1$ and $\tau_2$ are the characteristic relaxation time of the rapid decay term and the slow decay term, respectively. By fitting the PPF index curves shown in Figure 3c, it is deduced that $\tau_1 = 0.62$ s and $\tau_2 = 100.29$ s for the 450 nm light excitation, and $\tau_1 = 0.05$ s and $\tau_2 = 38.63$ s for the 635 nm light excitation, respectively. For both 450 and 635 nm light stimuli, there are clear distinctions between the rapid and the slow decay terms ($\tau_1$ and $\tau_2$). The distinctions between the rapid and slow decay terms and the timescale of the time constant are very similar to those of some biological synapses.\cite{22} The fitting results indicate that for the two different operating wavelengths, there exist two different types of PPF behavior in the studied photonic synapse.

2.3.2. Dual Short-Term Potentiation and Long-Term Potentiation (LTP)

In neuroscience, synaptic plasticity refers to the property that the strength of synaptic connections (synaptic weights) can be modulated by spike action potentials. There are two types of synaptic plasticity, which are short-term potentiation (STP) and long-term potentiation (LTP), corresponding to a temporary and a permanent change in the synaptic weight, respectively.\cite{24} It is generally believed that permanent changes in synaptic weight can be achieved through repeated stimulation at a suitable interval.\cite{25}

Figure 3d,e shows the different photocurrent responses of our device to a train of laser pulses with wavelengths of 635 and 450 nm, respectively. For the 635 nm laser, when applying four pulses, the photocurrent (conductivity) of the device experiences a sudden increase and then quickly decays to its initial state after the pulses are removed. Taking the conductivity of the device as the synaptic weight, this phenomenon is very similar to an STP behavior in a biological synapse. With the increasing number of stimulating pulses, no significant increase of photocurrent appears, and the response current quickly decays to its original state once the laser is removed. This phenomenon indicates that for the 635 nm light pulse stimulation, the photonic synapse exhibits only an STP behavior, rather than an LTP behavior.

Compared with the 635 nm laser, for the case of the 450 nm laser stimulation, the photocurrent increases notably with the number of light pulses increasing and then decays from a higher level after the light is turned off. Moreover, the more the pulses, the longer is the time is required for the current to decay back to its initial state. This behavior is very similar to an STP behavior in
a biological synapse whose short-term synaptic plasticity can last to the order of milliseconds to several minutes. Interestingly, when the stimulus light is turned off, the decay in the photocurrent does not seem to continue over time (as shown in Figure S4, Supporting Information). This behavior is very similar to an LTP behavior in a biological synapse. These results show that for the photonic synapse, STP to LTP transition can be achieved by merely increasing 450 nm stimulating light pulses.

In summary, there exist two types of synaptic plasticity in the same device (named as dual synaptic plasticity), and the dual plasticity can be switched to each other by choosing different stimulating light. The switchable synaptic plasticity is the basis of different neural functions in the same neural circuit.[22] In this study, the device shows different synaptic plasticities at different stimulating wavelengths, which is similar to a biological synapse. This feature is helpful for the photonic synapses to realize more nerve functions in a circuit.

2.3.3. Learning Experience and Associative Learning Behaviors

The learning experience behavior refers to the phenomenon that the human brain takes less time to relearn and recall what it has learned than the first time.[26] In classical conditioning, the transformation of a neutral stimulus to a conditioned stimulus can be achieved by pairing the neutral stimulus with an unconditioned stimulus, which is involved in associative learning.[27] It is believed that the learning experience and associative learning behaviors are closely related to the synaptic plasticity level of a synapse in the brain, playing critical roles in the learning and adaptability processes of the brain.[28,11c] Our photonic synapse presents the learning experience and associative learning behaviors.

Figure 3f shows the photocurrent response of the photonic synapse stimulated by spikes at 450 nm wavelength. It can be seen that when the second train of light spikes is applied to the synaptic device, only 20 spike stimuli are required to restore the device to the previous memory level produced by 80 spikes in the first train. This result means that our synaptic device can show a learning experience behavior.

The photonic synapse can also emulate the association learning behavior of a human brain. To demonstrate this behavior, we conducted Pavlov’s dog experiment using our device. Figure 4 shows the photocurrent response of the photonic synapse stimulated by 450 nm light and/or 300 mV voltage pulses. As shown in Figure 4a, the photocurrent response is very small when the photonic synapse is stimulated only by a 450 nm light pulse, simulating the ringing (conditional) stimulus and the no-slaver response of Pavlov’s dog to the ringing in a traditional condition experiment. When the photonic synapse is stimulated by a voltage pulse of 350 mV with the same pulse width alone, as shown in Figure 4b, the current response of the device far exceeds that in the case of light stimulation only, mimicking the food–sight (unconditioned) stimulus in the traditional conditional experiment. By applying the light and electrical pulses simultaneously, as shown in Figure 4c, the current response of the photonic synapse exceeds that of the light or electrical stimulus alone, mimicking the training stage using both bell ringing (conditional) and food–sight (unconditioned) stimuli simultaneously. It is worth noting that at this stage, the current response of the device is much larger than that stimulated by the light pulse.
only or the voltage pulse alone. After training, as shown in Figure 4d, the current response induced by the light pulse (ringing/conditional) stimulus is higher than that of the initial state (the red dashed line) before training, meaning that our device could successfully mimic the slave response of Pavlov’s dog during the ringing. Here, one can see that the difference in photocurrent response before and after training is not very large, which needs further optimization, and the data before and after training need to be processed for different network responses.

2.4. Mimicry of the Human Visual System

Figure 5a shows a schematic diagram of the process in which the human brain obtains information from the outside through the visual system, which involves the detection of information by the eye through light, the extraction of color by the retina, and the analysis of information by the central visual system. As shown in the figure, the retina does not simply pass along information about the patterns of light and dark that fall on it. Rather, the retina extracts information about different colors and sends it to the occipital lobe of the central vision system, so that the blue F in the E can be accurately recognized by the human brain.[1] A similar intelligent behavior can be observed in our device, as shown subsequently.

2.4.1. Colored Pattern Recognition

For the colored pattern recognition, 15 photonic synapses were randomly selected from a chip to identify and store images consisting of $3 \times 5$ pixel units. Each pixel unit of the synaptic array is stimulated in numbered order by a light pulse at 635 and 450 nm wavelengths, forming a capital letter “E” that is made of the blue “F” and the red “-“ as shown in Figure 5b. During the test, the postsynaptic current response is obtained with a reading voltage of 60 mV. At the beginning, the synaptic array detects the letter “E” with a different brightness and cannot distinguish between the blue and red, which is very similar to the human eye transmitting the detected information to the retina. However, after 10 s, the synaptic array detects the blue “F” in the letter “E” as if it can distinguish between the blue and red colors, which is very similar to the retina and central vision system, which can extract and analyze color information. These results demonstrate that our photonic synapses can mimic the human visual system, detecting optical signals and recognizing their wavelengths (i.e., red and blue colors). Such a color recognition function of the array could be attributed to the difference between the volatile and nonvolatile PC of the a-Si film excited by red and blue light. The present color-recognizing feature of our photonic synapses is completely different from other existing photonic synapses, which can only distinguish the grayscale of light information.

2.4.2. Grayscale Pattern Recognition and Memory

In psychology, “the multistore model” of human memory is still the most accepted memory model. In this model, the memory can be divided into sensory memory (SM), short-term memory (STM), and long-term memory (LTM), corresponding to different storage locations and maintenance time.[29] Interestingly, our photonic synaptic array can also enable recognition and memory for light and dark patterns similar to the human visual system. To experimentally demonstrate this psychological behavior, a $3 \times 3$ synaptic array was constructed to identify and store images consisting of $3 \times 3$ pixel units. As shown in Figure 6a, for the first light pulse stimulation, the synaptic array was unable to detect images encoded by different light intensities with a fixed

![Figure 5. a) Schematic diagram of human visual system identifying a colored pattern and b) colored pattern recognition analogous to the human visual system realized by ITO/a-Si/p++-Si photonic synapses.](image-url)
wavelength, corresponding to SM. However, when the number of light pulses was increased to 120, the photosynaptic array could reproduce images with different grayscale, corresponding to a process of rehearsal for STM. More importantly, after removing the light pulses for 180 s, the detected image was still clearly maintained, corresponding to LTM. A similar phenomenon for image memory can also be observed for the case of images encoded by different wavelengths, as shown in Figure 6b. This phenomenon can be attributed to the fact that for the stimulation at 635 nm wavelength, the photonic synapse can only act with the STP behavior. However, for the stimulation at 450 nm wavelength, it can behave with not only STP but also LTP. These observed phenomena are very similar to the human visual memory.

2.5. Influence of Reading Voltage

We have also conducted an experiment on the effects of the reading voltage $V_R$ on the photocurrent response and the persistent PC of the photonic synapse, respectively.

2.5.1. Adjustable Photocurrent Response

Figure 7a,b shows the effect of the applied read voltage $V_R$ on the photocurrent response of the photonic synapse stimulated by light at 450 nm wavelength lasting for 60 s. It is clear to see that the photocurrent response of the device linearly increases with the applied voltage increasing. A similar phenomenon can also be observed when applying a reversed bias voltage to the device, as shown in Figure S5, Supporting Information. This means that the photocurrent response can be adjusted by changing the reading voltage. Importantly, as shown in Figure 7b, in a relatively low-light radiation condition (with 180 mW cm$^{-2}$), by increasing the reading voltage to 720 mV, the device achieves a higher response than that achieved with a 700 mW cm$^{-2}$ light and a 360 mV reading voltage. This tunable characteristic of the photocurrent response could be explained by the increased carrier transport velocity and decreased electron–hole pair recombination efficiency under high bias voltage. This feature allows the photonic synapse to mimic the iris for light adapting and to work with stable performance in various light environments. It is worth mentioning that, as shown in Figure S5, Supporting Information, this adjustable characteristic is only related to the magnitude of the read voltage, regardless of the polarity of the read voltage.

2.5.2. Adjustable Persistent PC

Figure 7c shows the effect of the reading voltage $V_R$ on the persistent PC at constant intensities of stimulation pulses. When the reading voltage is small (60 mV), stimulations hardly cause a change in the current. After 100-pulse stimulations, the photocurrent immediately decays back to the initial state, corresponding to an STP behavior. Surprisingly, increasing of the reading voltage at the same stimulations could lead to a significant persistent PC with a long decay time, corresponding to an LTP behavior. This result indicates that the persistent PC can be adjusted by changing the reading voltage. The tunable persistent PC could be originated from the dependence of the photogenerated carrier trapping efficiency on the reading voltage.

As shown in Figure 7a, Figure S3, Supporting Information, the enhancement of the photocurrent response is at the expense
of power consumption. Fortunately, the signal-to-noise ratio does not increase with increase of the background current (as shown in Figure S6, Supporting Information).

Under the influence of factors such as emotions and interests, the human visual system has different concerns about external information, resulting in different levels of memory. The photonic synapse can mimic the visual system to achieve a similar memory behavior, thereby enabling the device to selectively remember information of interest. Figure 7d shows two pictures of an image of “+” recorded by a photonic synaptic array with reading voltages of 60 and 360 mV, respectively. Here, the reading voltages of 60 and 360 mV correspond to low and high interest to the same input image, respectively. As expected, under the same light stimulus, the image obtained by the reading voltage of 360 mV is much clearer than that of 60 mV.

3. Conclusion

A Si-CMOS-compatible ITO/a-Si/p⁺⁺-Si photonic synapse has been proposed and demonstrated. The device exhibits volatile and nonvolatile PC behaviors when stimulated by a laser of 635 and 450 nm, respectively. The volatile PC behavior mainly comes from the photoexcited electron trapped/detrapped by the intrinsic dangling-bond defects inside the a-Si film. In contrast, the nonvolatile PC behavior is related to new dangling-bond defects induced by light with a higher energy. This unique feature of persistent PC in the device enables the photonic synapse to recognize red and blue colors in a single device unit. Dual synaptic plasticity was demonstrated, which includes PPF and STP when stimulated by the 635 nm light and STP, LTP, and STP to LTP transition when stimulated by the 450 nm light. Artificial behaviors analogous to the human learning experience and associative learning have also been demonstrated. Based on the capability of a single device to distinguish red and blue colors, photonic synapse arrays were constructed to realize the detection of light information, the extraction of intensity and color information, and colored pattern recognition and memory. Moreover, the dual synaptic plasticity can be adjusted by changing the applied voltage lower than 1 V, making the device capable of selective detecting, processing, and memorizing of information of interest, which is repeatable in various light environments. In addition, the photonic synapse demonstrated here could functionally mimic biological synapses and the human visual system, rather than approaching a concluded principle. It is worth mentioning that the function demonstrated here could be extended to a broad wavelength range. Given its simple device structure, and full compatibility with the existing Si-CMOS technology, the photonic synapse demonstrated here shows excellent and vast potential for application in neuromorphic computing and advanced robot visual systems.

4. Experimental Section

Device Fabrication: The photonic synapse device with the structure of ITO/a-Si/p⁺⁺-Si was fabricated by depositing an a-Si thin film on a p⁺⁺-Si substrate (resistivity, 0.001–0.005 Ω cm) using a poly-Si target in a magnetron sputtering (RF) system. The RF power and the substrate temperature were kept at 100 W and at 300 °C, respectively. The sputtering was
performed under a 0.5 Pa working pressure along with a flow rate of 30 sccm at Ar:O₂ = 30:1. The ITO electrode layer was also deposited by RF magnetron sputtering using an ITO target, where the a-Si/p-Si sample was covered by a metal mask with a pattern of a circular array.

**Electrical Measurements:** All the I–V measurements were performed by a source meter system (Keithley 2636B) at read voltages of 60, 120, 180, 240, and 360 mV, under dark and light conditions, respectively. For the photocurrent–voltage characteristic, 450 and 635 nm lasers with variable intensities in the range of 0–1 W were used. Electrical measurements for mimicking the human visual system were performed by using 3 × 3 and 3 × 5 synapse arrays. For each synaptic array, photonic synapses were randomly selected and numbered. Each pixel unit of the synaptic array was stimulated in the numbered order by a light pulse at 635 and 450 nm wavelengths, forming the designed patterns. All the measurements were conducted under ambient conditions.

**Raman Analysis and SEM Characterization:** The Raman analysis was done by a RENISHAW inVia Raman Microscope in a backscattering configuration with a 514 nm laser at the power of 2 mW. The cross-section image of the device was obtained by SEM (HITACHI S-4800).

**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.

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