Chapter 3

Multifunctional Optoelectronic Device Based on Resistive Switching Effects

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Additional information is available at the end of the chapter

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Abstract

Optoelectronic resistive switching devices, utilizing optical and electrical hybrid methods to control the resistance states, offer several advantages of both photons and electrons for high-performance information detecting, demodulating, processing, and memorizing. In the past decades, optoelectronic resistive switching devices have been widely discussed and studied due to the potential for parallel information transmission and processing. In this chapter, recent progresses on the optoelectronic resistive switching mechanism, materials, and devices will be introduced. Then, their performance such as photoresponsivity, on/off ratio, as well as retention will be investigated. Furthermore, possible applications of the optoelectronic resistive switching considering logic, memory, neuromorphic, and image-processing devices will be summarized. In the end, the challenges and possible solutions of optoelectronic resistive switching devices for the next-generation information technology will be discussed and prospected.

Keywords: optoelectronic, resistive switching, memristor, memory, logic, neuromorphic

1. Introduction

The great success of transistor-based integrated circuits for modern computing provided exponential development of the way we live, work, and communicate. In the past decades, device scaling-down was an effective approach to maintain the continuous development of computing capabilities. However, the current semiconductor technology is facing the physical scale limitation and bandwidth bottleneck between memory and central processing unit (CPU) in modern-computing architectures, as shown in **Figure 1a**. Therefore, new devices, new architectures, and even new computing principles are eagerly desired to further enhance computing efficiency and capability in the post-Moore era.

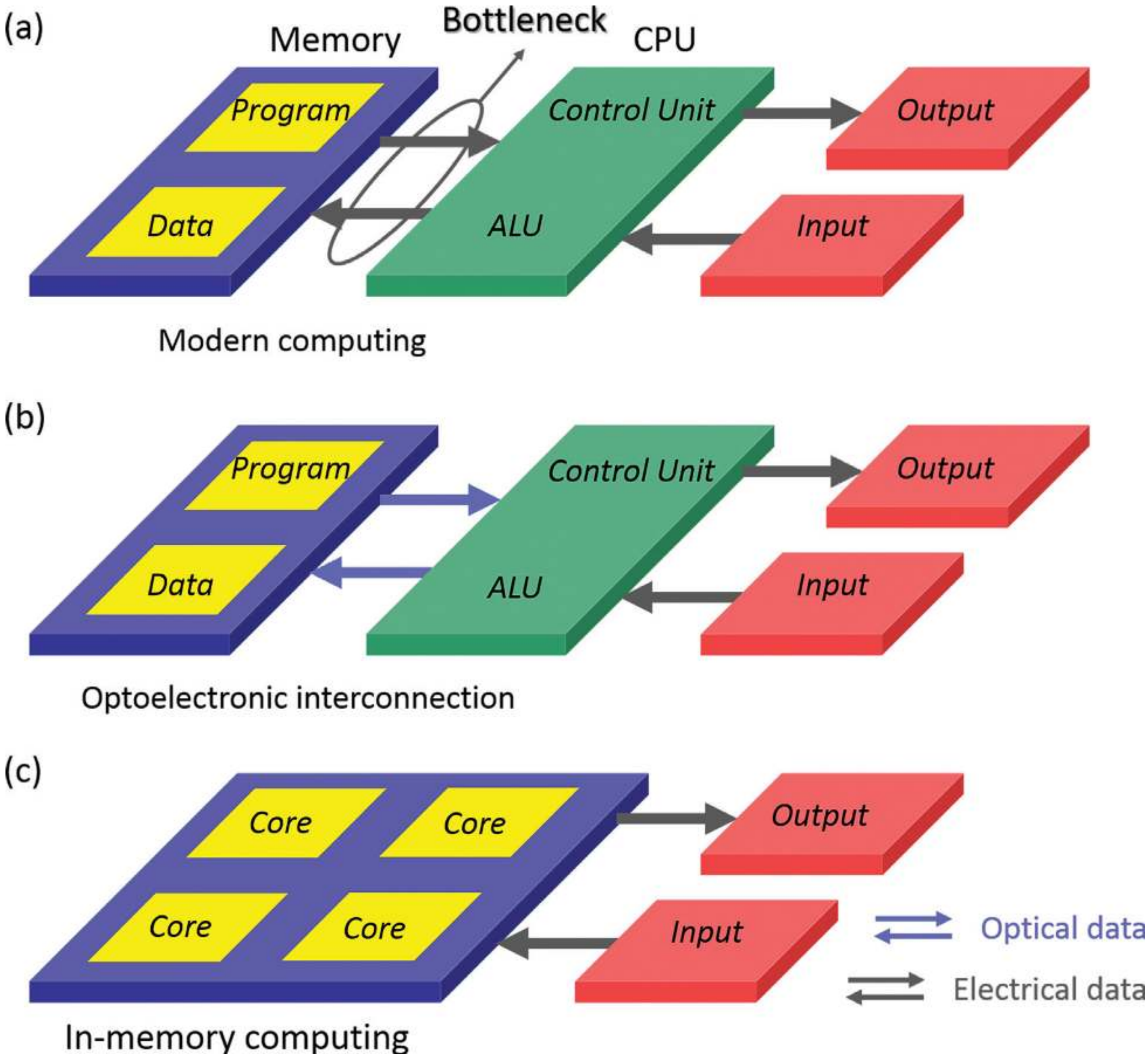


Figure 1. Possible approaches to optimize computing architectures. (a) Modern von Neumann-computing architecture. The separated memory and CPU are connected by data bus, which has frequency limitation. This architecture has low efficiency in data processing between memory and CPU. (b) Optical communication between memory and CPU will overcome the frequency limitation and increase its efficiency. (c) Parallel data processing and memory using memristor-based architecture.

Optoelectronic interconnection is a feasible method to overcome the bottleneck by transmitting data between memory and CPU *via* photons, which have a much faster transporting speed, a higher bandwidth, no Joule heat, and no interference over electrons [1–10]. As shown in **Figure 1b**, optical communication between CPU and memory will fully meet the demands of modern-computing architecture in high-frequency data communicating and processing [1–10]. On the other hand, memristor (memory + resistor), a simple two-terminal electrical switch with nonvolatile reconfigurable resistance states, has been considered as one of the promising approaches to construct new architecture with the novel in-memory computing (**Figure 1c**) [11–20]. Due to the arbitrary nonvolatile resistance states, memristor-based architectures provide the high potential for integrating processor and memory together, which eliminates the bottleneck between memory and processor in the modern von Neumann-computing architecture, thus allowing high parallel data processing [21–26]. However, the electronic memristor-based architecture still has bandwidth limitation in high-frequency data communicating between different modulators.

The combination of photons and memristor-based circuits will integrate the advantages of photons in a high-speed data transmission and memristors in parallel in-memory computing and may open up a new era for future computing owing to the high bandwidth and low-power consumption. Moreover, the optoelectronic-based memristive system will extend the application of memristor-based architecture to image or visual information processing. As shown in **Figure 2**, with the increasing demands of mobile computing in human daily life, wearable devices, health-care devices, and human-machine interacting devices including intelligent image sensor, video monitor, invisible touch screen, electronic eyes, wearable heart or blood monitoring and display devices, smart processor, and even brain-implantable devices will be more and more important for an efficient and comfortable way for our better life, body health, daily work, and communication [27–32]. The optoelectronic memristor-based architecture, wherein both photons and electrons are used for parallel data processing and communicating between input-output (I/O) devices and the in-memory processor, may provide such a platform for the mobile computing.

In this chapter, recent developments on optoelectronic memristor materials and devices, and applications including logic, memory, memristor, and neuromorphic devices will be summarized, then their capability in future optoelectronic on-chip interconnection, in-memory computing, brain-inspired computing, and visual information processing will be evaluated.

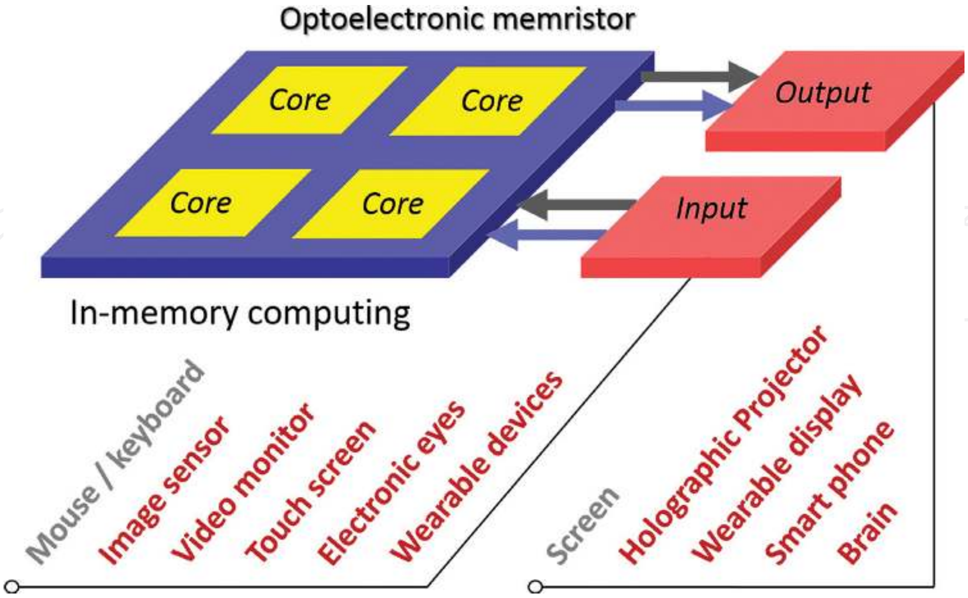


Figure 2. Possible optoelectronic memristor-based-computing architecture. In the in-memory processing unit, a core has the ability to process and store data *in situ*. Both photons and electrons can achieve the communication between the cores and I/O devices.

These optoelectronic approaches may help to overcome the limitations and bottleneck in the current computing devices and architectures, as well as contribute to efficient data analysis, cognitive computation, and artificial intelligence.

2. Optoelectronic resistive switching materials and devices

Resistive switching memory (memristor) is a simple two-terminal device with three-layered structure—two electrode layers for electrical signals input and output, and a “memory” layer in between. The resistance of the “memory” layer can be dynamically reconfigured by voltage- or current-induced ion implantation, interfacial charge accumulation, and so on. Usually, the electrodes are metal or oxide, such as Ag, Au, Pt, Ta, Ir, Cu, ITO, and so on, which will affect the resistive switching behavior by their different work function, electron affinity, electrochemical energy, and so on [33, 34]. For the “memory” layer, various kinds of materials have been used, including binary oxide, nitride, perovskite, low-dimensional materials, and organic materials [35–45]. Due to the simple structure and excellent performance including high-density integration, high-speed, and low-cost fabrication for logic, memory, and neuromorphic applications, memristor has been considered as one of the most promising next-generation information technologies [19, 20, 46].

Meanwhile, optical interconnection with high data transmission speed and no Joule heat or interference has proved to be another effective approach to overcome the data transmission bottleneck between memory and processor. Moreover, combining the advantages of photons and electrons in an optoelectronic memristor will allow highly parallel data transmission and processing, as well as extending the application for image recognition and visual information processing. In the optoelectronic memristor (**Figure 3**), both optical and electrical signals are able to modulate the resistance states of a “memory” layer, which is sensitive to both electrical

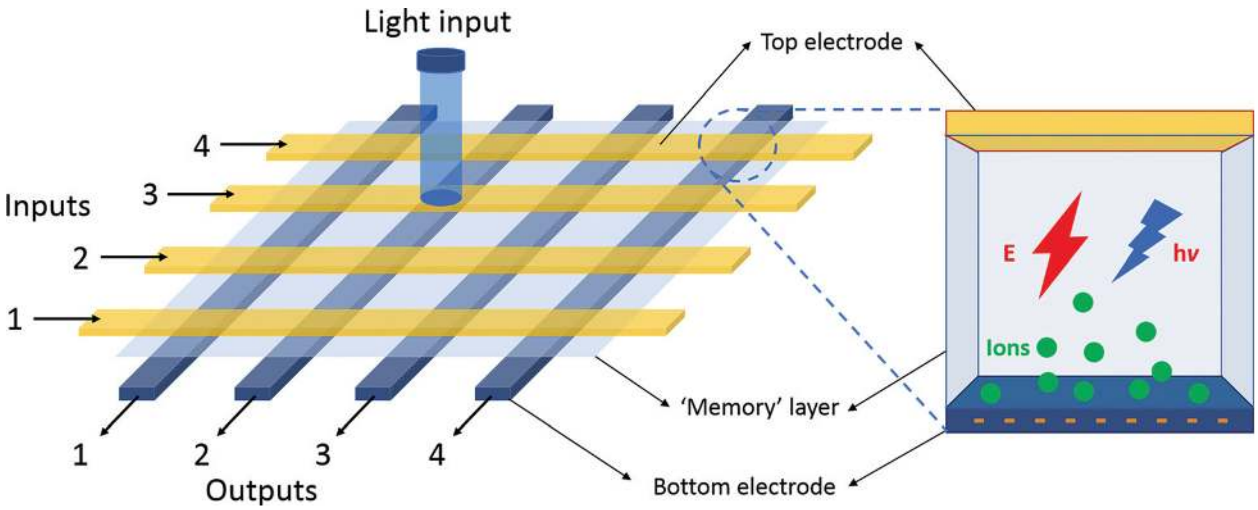


Figure 3. Optoelectronic memristor structure and mechanism.

and optical signals. Therefore, photosensitive semiconductor materials will meet the demands of the "memory" layer, such as silicon, cerium oxide, zinc oxide, perovskite, low-dimensional materials and organic materials, and so on [47–52].

In 2012, Ungureanu et al. reported a reversible light-controlled resistive switching memory in metal/Al_2O_3/SiO_2/Si structure, with the photogenerated electrons injection from Si to Al_2O_3 at sufficient positive bias and charge removal at negative bias [53]. In this work, the light pulses with different wavelength and intensity were utilized to study the photoresponsive behavior of the memory, as well as to achieve multilevel and multifunctional optoelectronic resistive switching memory. This work proved that the metal/Al_2O_3/SiO_2/Si-structured device can work as a multifunctional optoelectronic device including information storage and light sensing, meanwhile, offering the possibility for extra optical degree to be exploited in resistive switching memory devices.

Besides Si, ZnO is another kind of typical photosensitive semiconductor and has been widely studied for UV detectors, as well as resistive switching memories [35, 49]. Based on the semiconducting and photosensing properties of ZnO, Bera et al. combined the resistive switching and persistent photoconductivity (PPC) together in ZnO/NSTO Schottky junction in 2013 [54]. The photo-induced interfacial positive oxygen vacancies movement under electric field can lower the interfacial barrier and modulate the nonvolatile multilevel resistance states, thus realizing persistent photoconductivity and resistive switching. Annealing process was able to erase the PPC to its initial state. The results in this work provided a general route to achieve multifunctional devices by integrating functional materials.

Most recently, two-dimensional materials, such as graphene and MoS_2, have drawn much more attention due to their promising properties for the next-generation information technology. In 2014, Roy et al. reported a multifunctional photoresponsive memory based on graphene-MoS_2 hybrid three-terminal structure, wherein a gate was used to maintain and erase the trapped charges, thus achieving erasable persistent photoconductivity for optoelectronic memory devices (**Figure 4**) [55]. In addition, different gate amplitudes and light intensities were used to achieve multilevel memory. This work showed that the novel two-dimensional materials are promising for multifunctional optoelectronic memory.

Besides, organic materials have many advantages including low-cost fabrication, flexibility, and bandgap tunability, which are promising for optoelectronic memory devices. In 2012, Ye reported an optoelectronic multilevel resistive switching memory shown in **Figure 5** using a metal-conjugated donor-bridge-acceptor (DBA) molecule, which is responsive to both optical and electrical stimuli [56]. Under dark condition, the Al/metal-conjugated DBA/ITO-structured devices showed a bi-stable resistive switching behavior. When illuminated by UV light, a middle state was induced by the sub-step charge transfer process through the cooperation of UV light and electric field. This work may open up new opportunities of organic materials for designing multifunctional optoelectronic memory.

In a short summary, photo-induced charge trapping and detrapping play the key role in optoelectronic resistive switching effect. Other than the materials stated earlier, carbon nanotube, complex oxide, perovskite, quantum dots, and so on, also show optoelectronic resistive

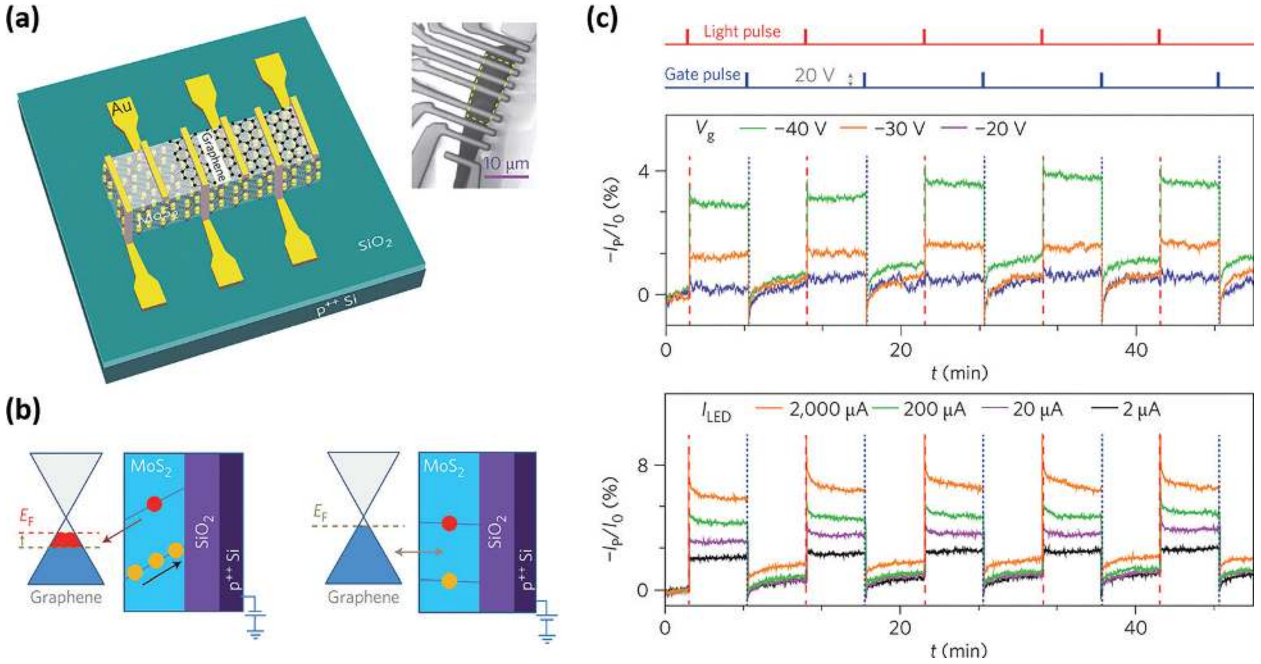


Figure 4. Photosensitive memory based on MoS_2/graphene hybrid structure. (a) Materials and devices structure. (b) Photoresponse mechanism. (c) Multilevel optoelectronic memory via modulating gate bias and light intensity. Reproduced with permission from Ref. [55]. Copyright 2014 Nature Publishing Group.

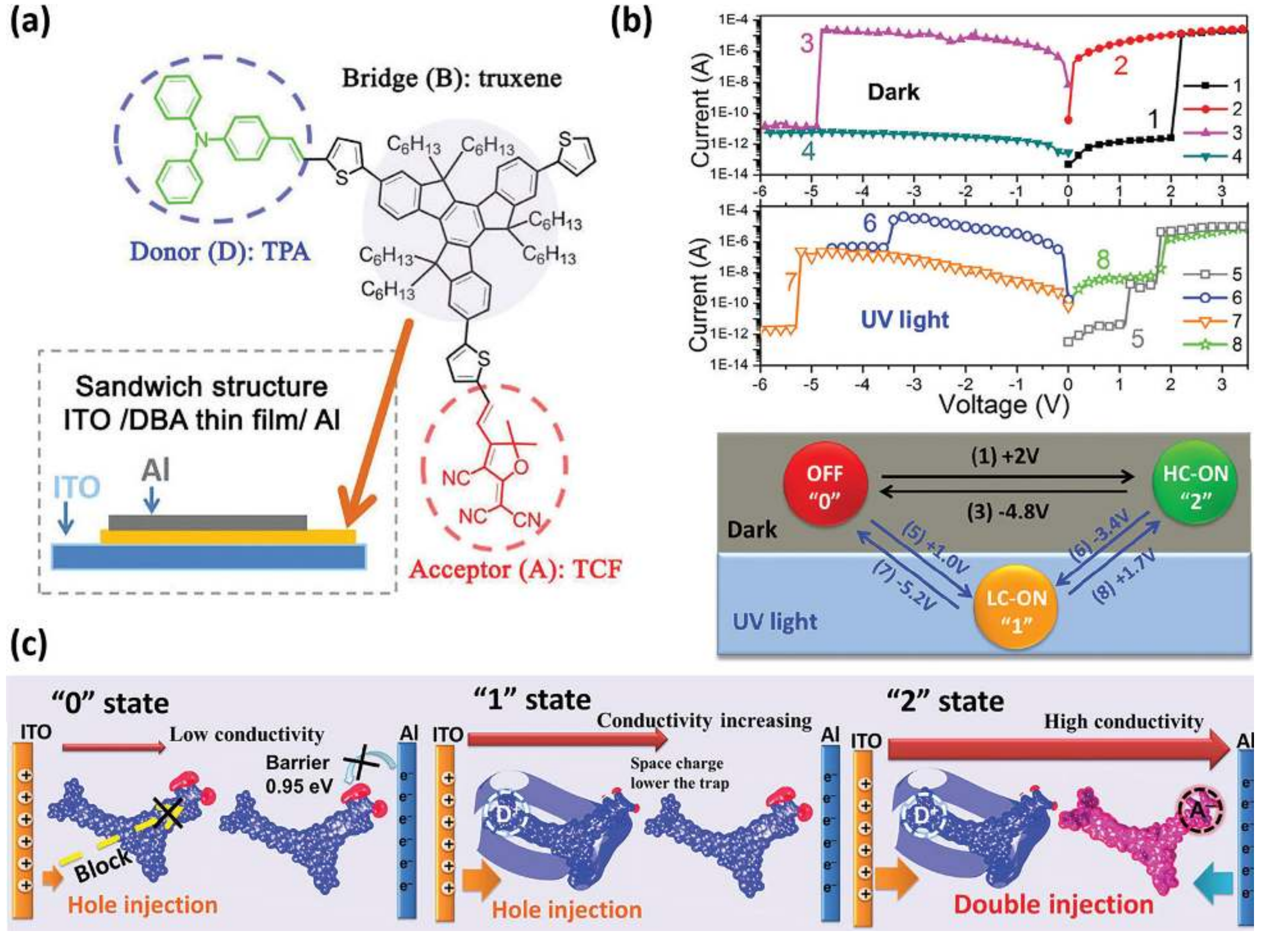


Figure 5. Organic optoelectronic resistive switching memory. (a) Materials and devices structure. (b) Resistive switching behaviors under dark and UV light illuminations. (c) Optoelectronic switching mechanism. Reproduced with permission from Ref. [56]. Copyright 2012 American Chemical Society.

switching effects [57–60]. The applications of optoelectronic memristor including logic, memory, neuromorphic devices, and their performance will be discussed in the following sections.

3. Multifunctional optoelectronic logic and memory

Optoelectronic memristors, allowing electrical and optical signals to modulate the states, are capable of functioning as sensor, decoder, arithmetic unite, logic, and memory devices for data communication, integrated photonics, in-memory computing, and brain-like computing. In this section, optoelectronic logic and memory devices will be discussed and their performance will be evaluated.

Logic is one of basic and most important functions in the integrated circuits [61–65]. Therefore, the realization of optical and electrical-mixed logic is the first step for optoelectronic circuits. For example, Kim et al. reported a series of optoelectronic logic devices based on single-walled carbon nanotube (SWNTs)/silicon junctions [57]. As shown in **Figure 6a**, in the SWNTs/Si junction, voltage and light pulse are inputs and currents are outputs. Due to the photoresponse under voltage bias, the output current is much higher (logical "1") when both voltage and light are applied to the junction than the current when only one or neither is applied (logical "0"), thus functioning as an "AND" gate (**Figure 6b**). Similarly, "OR" gate and 2-bit adder functions were also achieved using two junctions. Furthermore, utilizing four junctions with specialized

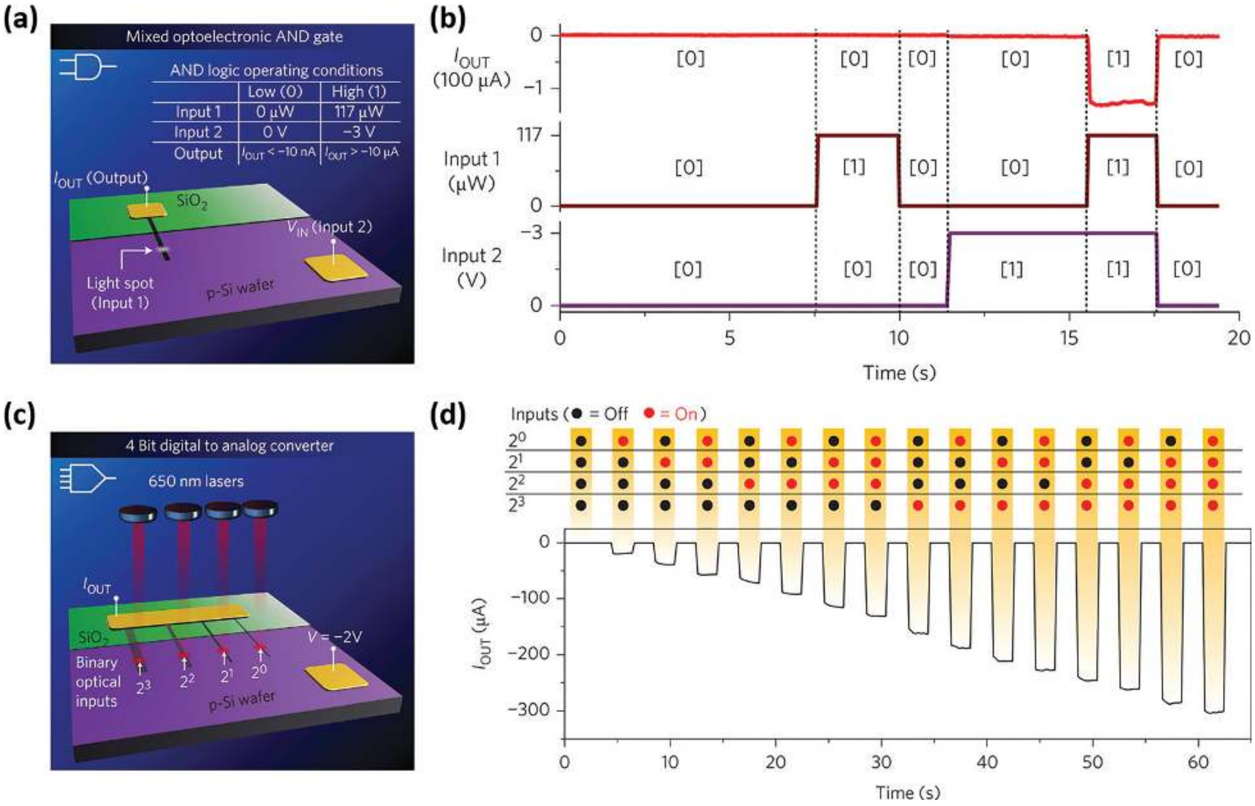


Figure 6. Optoelectronic logic gates. (a) "AND" logic with one light input, one voltage input, and a current output. (b) Output current value of the "AND" gate. (c) 4-bit digital-to-analog converter with light illuminating on four junctions with different areas. (d) Output current value of the 4-bit digital-to-analog converter. Reproduced with permission from Ref. [57]. Copyright 2014 Nature Publishing Group.

active areas, a 4-bit digital-to-analog converter (DAC) was demonstrated, as shown in **Figure 6c** and **d**.

Memory is another basic and important function in integrated circuits. If an optoelectronic memory device can integrate other specific functions such as photo signal detection, demodulation, arithmetic, and even logic in a single device, where the processed data can be stored *in situ*, then it will lower the complexity of integrated circuits and allow highly parallel computation. To achieve this goal, in 2015, we studied the ITO/CeO_{2-x}/AlO_y/Al-structured photoresponsible junction and designed a multifunctional optoelectronic resistive switching memory (OE-memory) with integrated photodetection, demodulation, and arithmetic [66]. As shown in **Figure 7**, CeO_{2-x} works as a photon-absorbing layer, and the electrons trapped in the defects in the CeO_{2-x} layer near the interface can be excited by photons and leaving positively charged oxygen vacancies, which will lower the effective barrier and decrease the resistance of the junction persistently with a thinner barrier. At the CeO_{2-x} and Al interfaces, a 5-nm native oxide layer formed and acted as an insulating layer to decrease the dark current. ITO works as a transparent and conductive top electrode and Al is the bottom electrode. In this simple two-terminal structure, persistent photoconductivity was observed as shown in **Figure 8**. The nonvolatile resistance states can be reversibly switched between high resistance state (HRS) and low resistance state (LRS) by visible light pulse and voltage, thus acting as an optical-write and electrical-erase memory.

Further study of this optoelectronic memory showed the wavelength and intensity-dependent photoresponse, which was utilized to design an optical signal detector and demodulator. As shown in **Figure 9**, with two-digit information (wavelength and intensity) per light pulse, four pulses with blue or green and 4 or 6 pW/μm^2 are capable of carrying

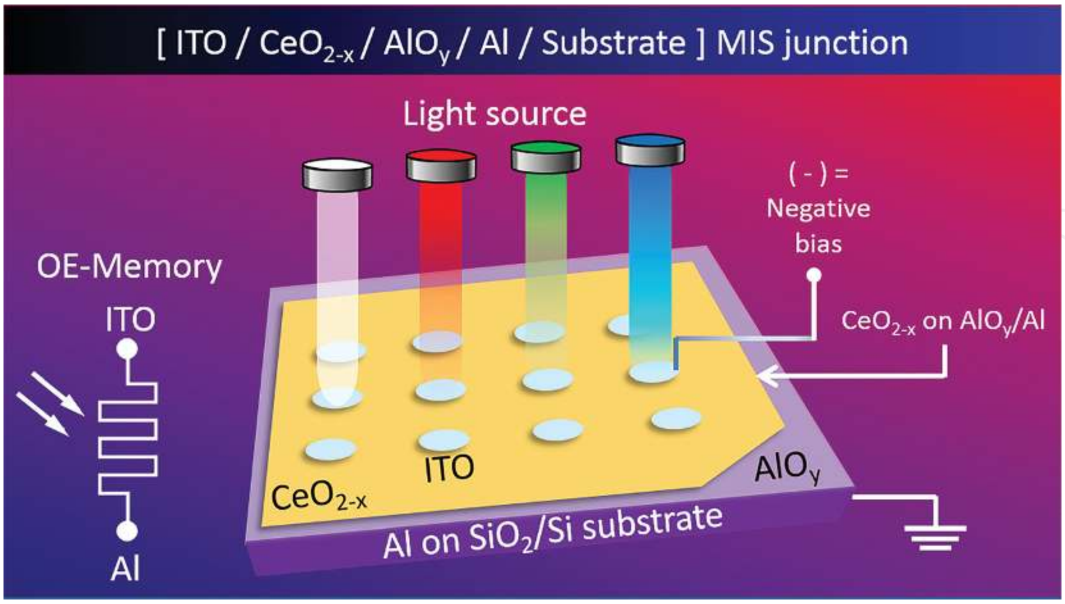


Figure 7. Schematic illustration of the optoelectronic memory (OE-memory) based on the ITO/CeO_{2-x}/AlO_y/Al junction and its operation principle. Reproduced with permission from Ref. [66]. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

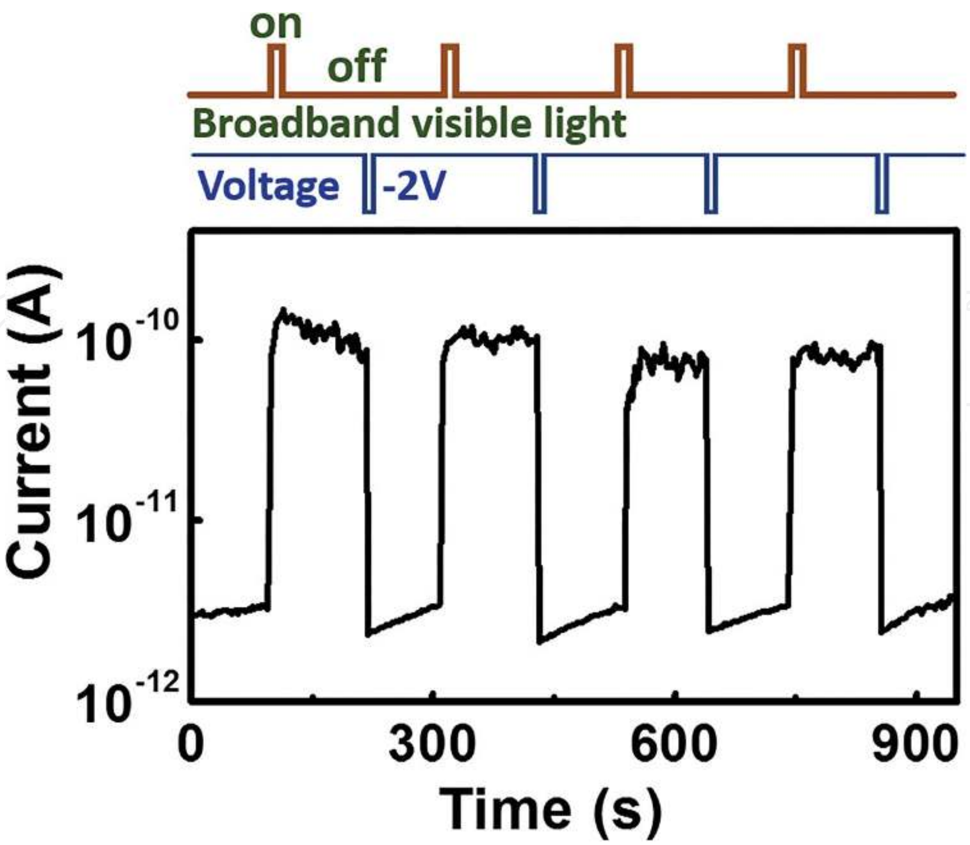


Figure 8. Reversible nonvolatile optoelectronic resistive switching behavior. A visible light pulse switches the structure from HRS to LRS and a voltage pulse switches the structure from LRS to HRS. Reproduced with permission from Ref. [66]. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

8-digit information, which is one letter according to the ASCII code, and can be demodulated and stored into four resistance states. Therefore, optical signal detecting and demodulating functions have been achieved in this simple optoelectronic memory. Furthermore, the photoconductance is increasing linearly with light pulse number (**Figure 10a**). Based on this linear relationship between photocurrent and the number of light pulses, counter and adder of the number of light pulses can be realized and the details are shown in **Figure 10b**. Meanwhile, the output results after counting or adding the pulse number can be stored as resistance states, thus allowing the integration of simple arithmetic and memory functions in a single cell. To evaluate the memory retention performance, multilevel resistance states were measured continuously, and after 10^4 s, the resistance states remain distinguishable (**Figure 11**). Above all, the simple optoelectronic structure is capable of functioning as optical signal detection, demodulation, arithmetic, and storage. These results demonstrate the possibility of using multifunctional optoelectronic devices for future integrated photonics, parallel processing, and in-memory computing [66].

In our recent work, to further exploit the integration of logic functions into the memory [67], electrically resistive switching and the persistent photoconductivity are combined to modulate the resistance states (**Figure 12**) [68].

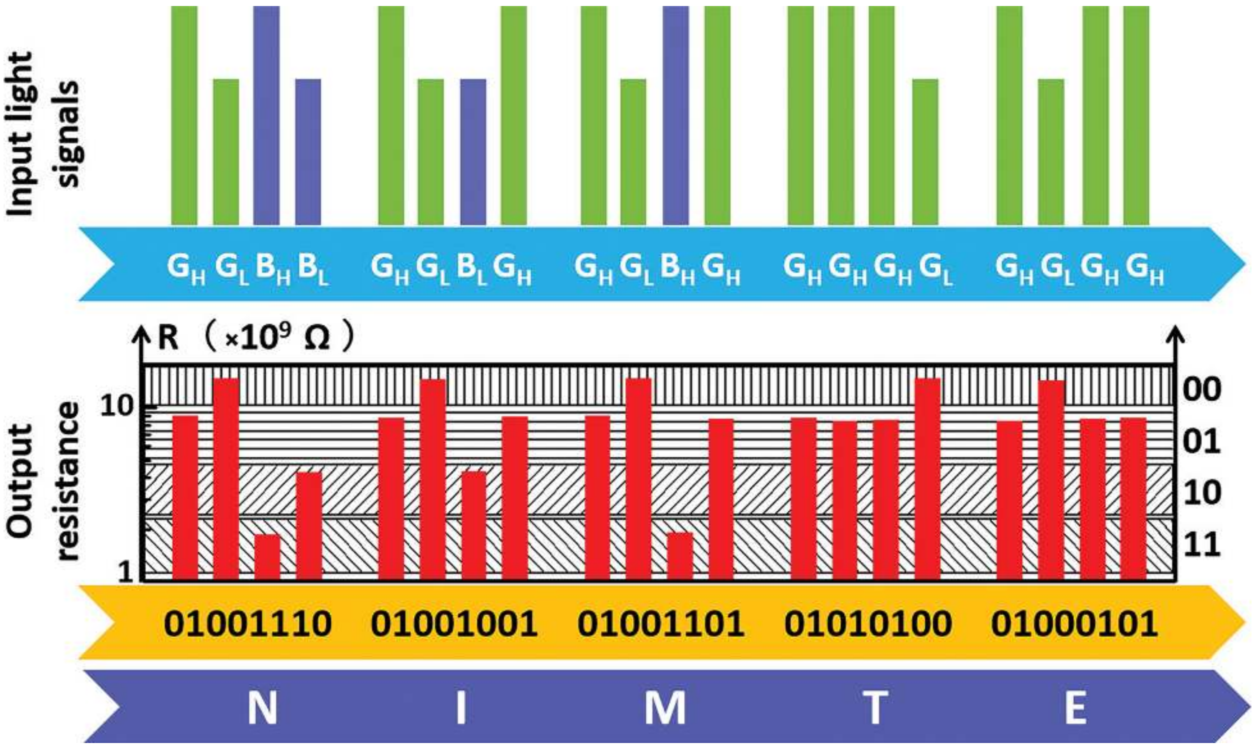


Figure 9. Proof-of-concept demonstration of demodulating function. The work "NIMTE" encoded in light pulses according to ASCII code can be demodulated and stored into nonvolatile resistance states.

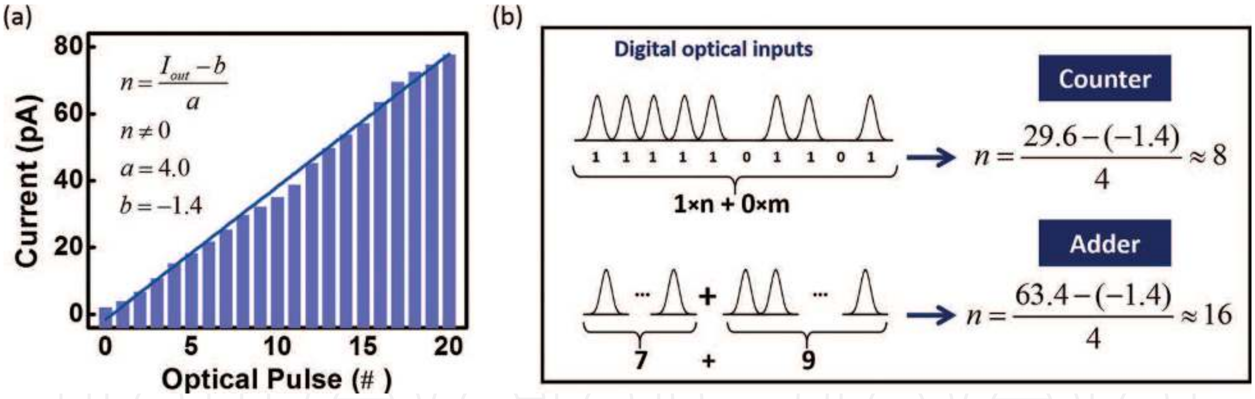


Figure 10. Optoelectronic arithmetic function in the OE-memory. (a) Photocurrent after a series of identical light pulses. (b) Simple counter and adder functions demonstration based on the linear relationship between photocurrent and light pulse number shown in (a). Reproduced with permission from Ref. [66]. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Using one light pulse and one voltage pulse as logical inputs and current as logical output, an "AND" gate was achieved. Only when both a light pulse and a voltage pulse are present, the output value is larger than 150 nA, which is logical "1," otherwise, the output current is lower than 150 nA, which is logical "0." Furthermore, the "AND" gate can be reconfigured to "OR" gate when a light-write pulse applied before logic operations, thus allowing the OE-memory functioning as an optoelectronic nonvolatile reconfigurable logic gate (**Figure 13**). Besides the reconfigurable "AND" and "OR" logic functions, "NOT" operation and a complicated logic operation were achieved by introducing another electrical-erase pulse, as well as optical adder

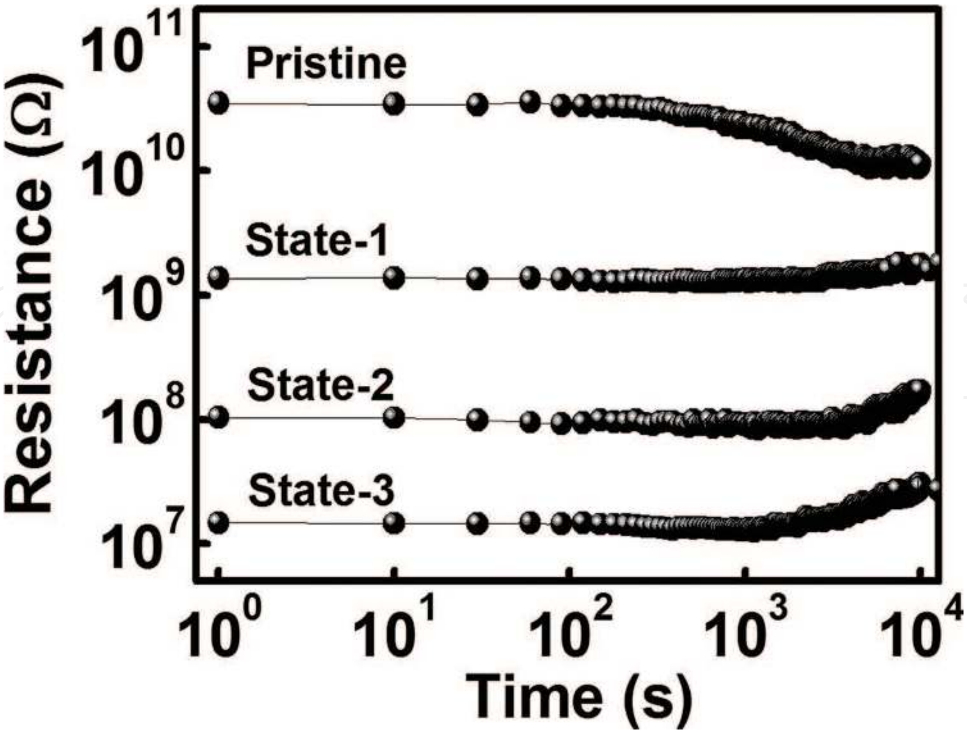


Figure 11. Retention characteristic of four states programmed by light pulses with different intensities. Reproduced with permission from Ref. [66]. Copyright 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

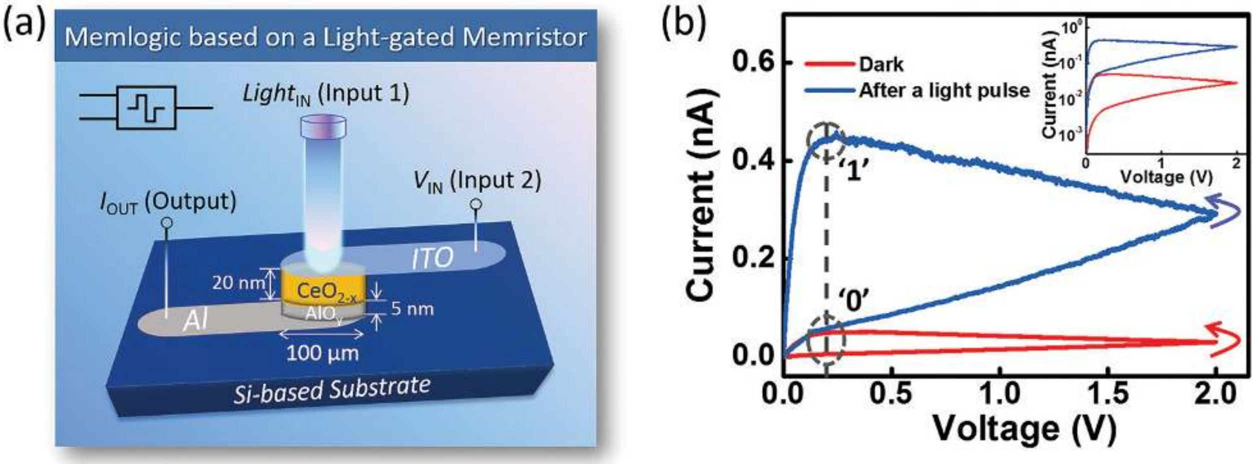
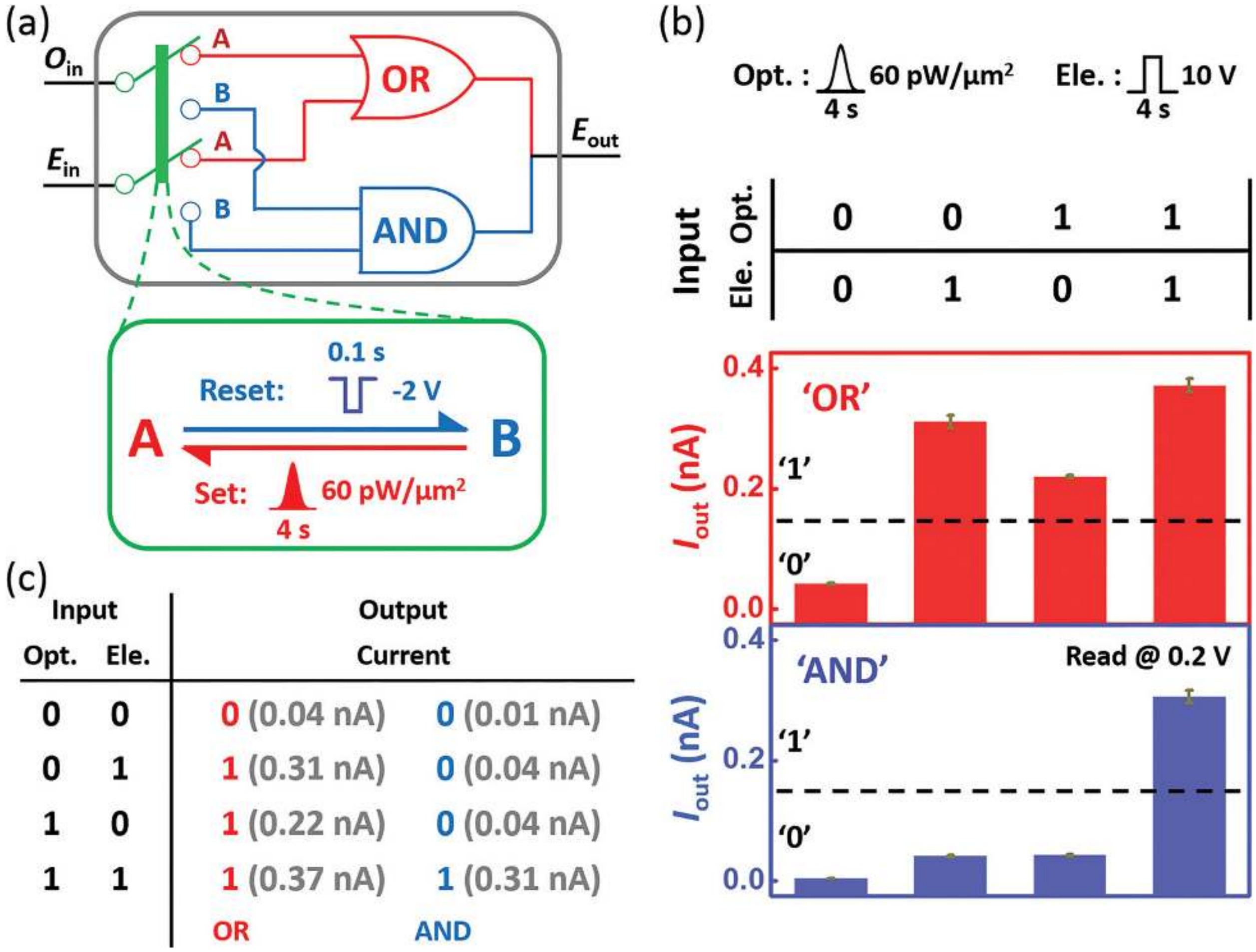


Figure 12. Schematic illustration of the structure (a) and optoelectronic resistive switching behaviors (b) of the memlogic. Reproduced with permission from Ref. [68]. Copyright 2017 American Chemical Society.

and digital-to-analog converter (DAC) functions were achieved by using two light pulses as inputs. We name this nonvolatile reconfigurable logic gate as "memlogic," memory of logic operations and outputs.

Based on the optoelectronic reconfigurable logic functions, a proof-of-concept reconfigurable image-processing and memorizing functions were demonstrated, as shown in **Figure 14**. Two images with "X" and "Y" shapes of visible light pulses are used as inputs into a 5 by 5 memlogic array and current map as output (**Figure 14a**). When all the cells were reset to "AND" logic state,



Input		Output	
Opt.	Ele.	Current	
0	0	0 (0.04 nA)	0 (0.01 nA)
0	1	1 (0.31 nA)	0 (0.04 nA)
1	0	1 (0.22 nA)	0 (0.04 nA)
1	1	1 (0.37 nA)	1 (0.31 nA)
		OR	AND

Figure 13. Memlogic operation of reconfigurable "AND" and "OR" gates. (a) Reconfiguration operation of "AND" and "OR" gates. (b) Output current value of the memlogic. (c) Truth table of the memlogic. Reproduced with permission from Ref. [68]. Copyright 2017 American Chemical Society.

the processor can find the same part in different images and we named it SAME FINDER (**Figure 14b**). When all the cells were set to "OR" states, the processor can find the parts either in 'X" or "Y" images and we named it as ALL FINDER (**Figure 14c**). Therefore, the single memlogic array can realize two different image processing, as well as image storage functions.

Above all, the memlogic is capable of performing different reconfigurable logic functions and nonvolatile memory and may provide a new method for reconfigurable in-memory computing, integrated photonics, and artificial intelligence [68].

In summary, for information technology application, these optoelectronic resistive switching devices need to be optimized to improve their performance including the photoresponsivity, speed, memory window, retention time, endurance, fabrication cost, reliability, yield, and so on. Here, the summary of some basic parameters is shown in **Table 1**. The photoresponsivity measures the input–output gain in a photoresponsive system and means the electrical output per optical input. On/off means the memory window. Speed represents how fast the device can work. For memory or logic applications, the speed needs to be at ns level. Here, the speed of these optoelectronic resistive switching devices is not enough and needs to be improved exponentially. Possible methods will be increasing the build-in electric field to accelerate the

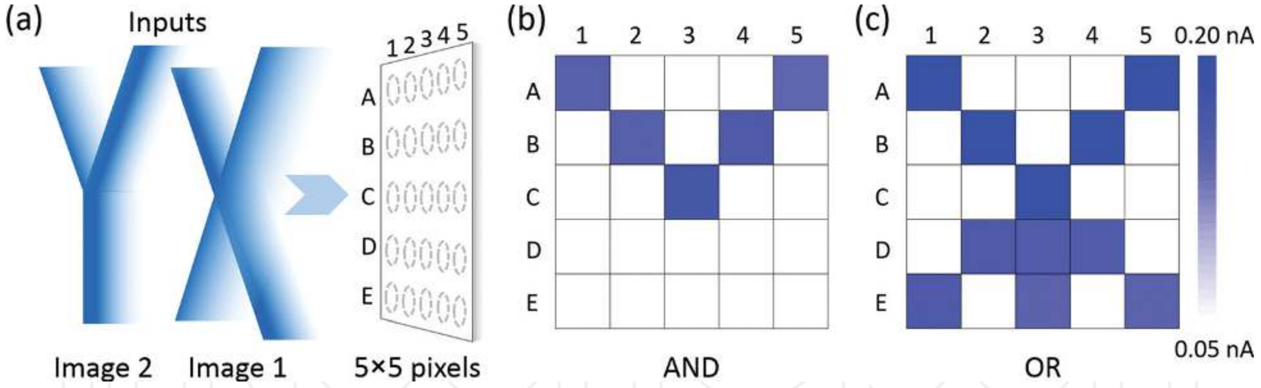


Figure 14. Proof-of-concept demonstration of reconfigurable image processing. (a) 'X' and 'Y″ shape of light image were inputs and current map was the output. (b) Image same finding function when all the memlogic cells are at HRS and (c) image all finding functions when all the memlogic cells are at LRS. Reproduced with permission from Ref. [68]. Copyright 2017 American Chemical Society.

Structure	PPC/PC/PR	Responsivity	On/off	Speed	Retention	References
Pd/Al_2O_3/SiO_2/Si	PC	_	10^3	_	_	[53]
Ti/ZnO/NSTO	PPC	_	>10^3	~100 s	>10^4 s	[54]
Al/Organic/ITO	PR	_	10^6	_	5 × 10^4 s	[56]
ITO/CeO_{2-x}/AlO_y/Al	PPC	1 A/W	10^3	~10 s	~10^4	[66, 68]

Notes: PPC, persistent photoconductivity; PC, photoconductivity; PR, photoresponse.

Table 1. Characteristics of the typical photoresponsive memristors.

photo-induced charge separation by using electrodes with a higher work function or increasing the defects concentration. Retention means how long the state can maintain. From this table, we can see that the performance especially the speed should be improved immediately.

4. Optoelectronic neuromorphic devices

Artificial neural network is one of the most promising ways to achieve brain-like computing and has been an attractive area especially for memristors as the similar ionics-based mechanisms and stochastic dynamics with neurons [69–87]. Optoelectronic memristors provide another degree of freedom by light to control their states, which means light pulse can be utilized as stimuli to control artificial synapse weight and proceed with synaptic behaviors simulation. Moreover, optoelectronic memristor-based networks allow optical communications among nodes and will reduce power consumption, increase communicating speed, and efficiency. Recently, several research groups have proposed optoelectronic artificial synaptic devices based on persistent photoconductivity for neuromorphic computing. In 2010, Agnus et al. reported an adaptive architecture based on optically gated carbon nanotube transistors, which allow optical write and electrical program processes to control the resistance states [88]. The programmed states are nonvolatile and can be used to store synapse weight in adaptive architectures. More specific synaptic behaviors simulation such as short-term memory (STM), long-term memory (LTM), facilitation, and spike-timing-dependent plasticity (STDP) have been achieved in IGZO-based persistent photoconductive devices by Lee in 2017. They also showed the photoenergy and frequency-dependent plasticity. These basic synaptic behaviors simulation will promote the development of optoelectronic artificial neuro-network [88].

As we all know, human eyes are the most important media to receive visual information from surroundings and provide humans with the ability to recognize objects. In human visual system, the eyes receive light signal and convert it to electrical pulses signal, which can be detected by visual neuron and analyzed or memorized by visual cortex in the brain. In general, two parts for sensing and processing of visual information form the visual system. In recent years, inspired by human visual system, several kinds of artificial visual systems have been proposed to simulate eyes for visual information processing, retinopathy therapy, and reproduction of visual system [27, 89–91]. Usually, photodetector array acts as the retina to sense the light that converts it to electrical signal for image processor, visual neuron, and cortex. For example, as shown in **Figure 15**, Mathieson et al. reported a photovoltaic retinal prosthesis, which is capable of detecting light signal, imaging on silicon photodiode array, and processing the detected image. The demonstration of fully integrated wireless implant may reproduce the vision to the patients with retina diseases [27]. However, this photodiode-based system lacks the function of memorizing of image information. Therefore, memristor may be applicable for image memory. In 2017, Chen et al. reported an artificial visual memory system consisting of an imager and a memory. The UV image can be detected by In_2O_3-based imaging system and stored by Al_2O_3-based

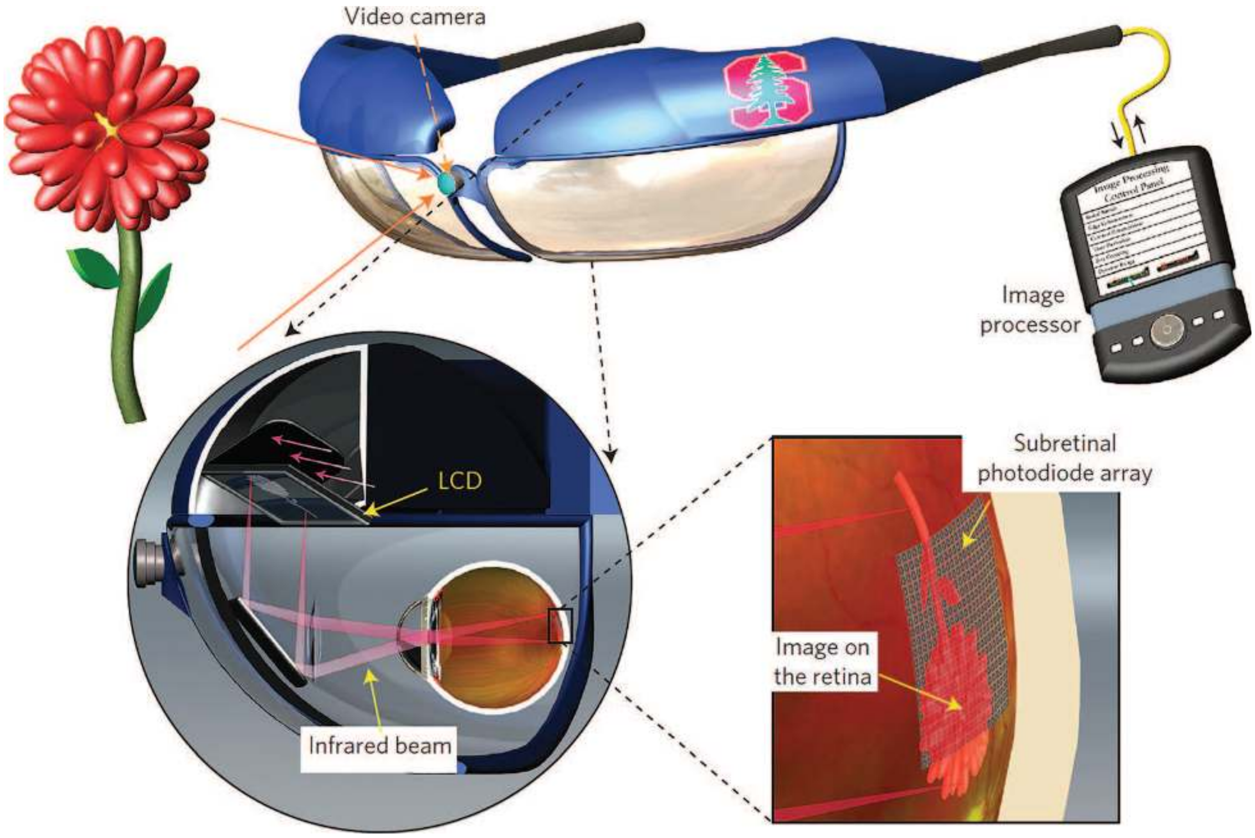


Figure 15. An artificial visual system based on silicon photodiode. Reproduced with permission from Ref. [27]. Copyright 2012 Nature Publishing Group.

processing and memory system [92]. The design of this artificial visual system provides a novel approach to integrate different devices to achieve more multifunctional bioinspired systems.

Thanks to the reported works, these novel promising optoelectronic synaptic devices have been proposed and achieved and will be the first step for optoelectronic neural networks. Optoelectronic artificial neural networks provide the additional advantage of optical communication into memristor-based neuromorphic architectures. Based on the previous research, the next plan should focus on improving their performance, exploiting optoelectronic artificial neural networks, and optogenetic neural networks.

5. Other approaches for multifunctional resistive switching

Besides the optical-based resistive switching memories, electrical- and magnetic-based resistive switching devices are also interesting and attractive due to their important and promising physical properties and applications [93].

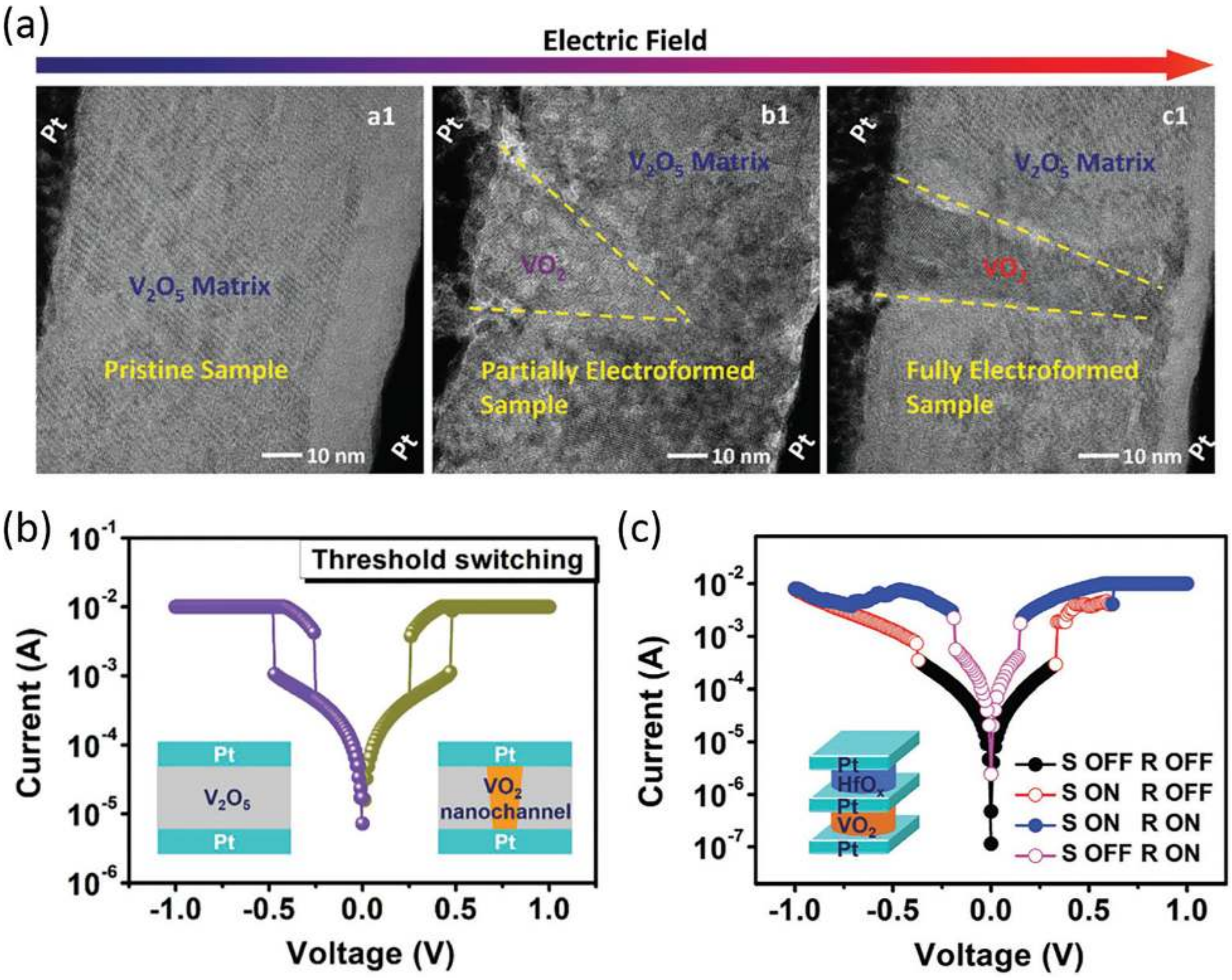


Figure 16. Nanochannel-based selector mechanism and its performance. (a) Transmission electron microscopic (TEM) image proved the electric field-induced VO_2 nanochannel formation in V_2O_5 matrix. (b) Threshold switching behavior. (c) Resistive switching behavior of the 1S1R structure. Reproduced with permission from Ref. [94]. Copyright 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Recently in our group, a nanochannel device was designed in V_2O_5-based selector via electric field-induced ion migration [94]. As shown in **Figure 16**, this electric field-induced nanochannel demonstrates a sharp and reliable metal–insulator transition (MIT) with a 17 ns switching speed, an 8 pJ energy consumption, and less than 4.3% variability. By combining with one HfO_x-based memristor, the 1S1R structure device can ensure the correct reading of the memory states continuously for 10^7 cycles, therefore demonstrating its great possibility to overcome the crosstalk problem in high-density crossbar memory. This work proved that electric-field-induced ion migration at the nanoscale is an effective approach to optimize device performance or design novel conceptual devices.

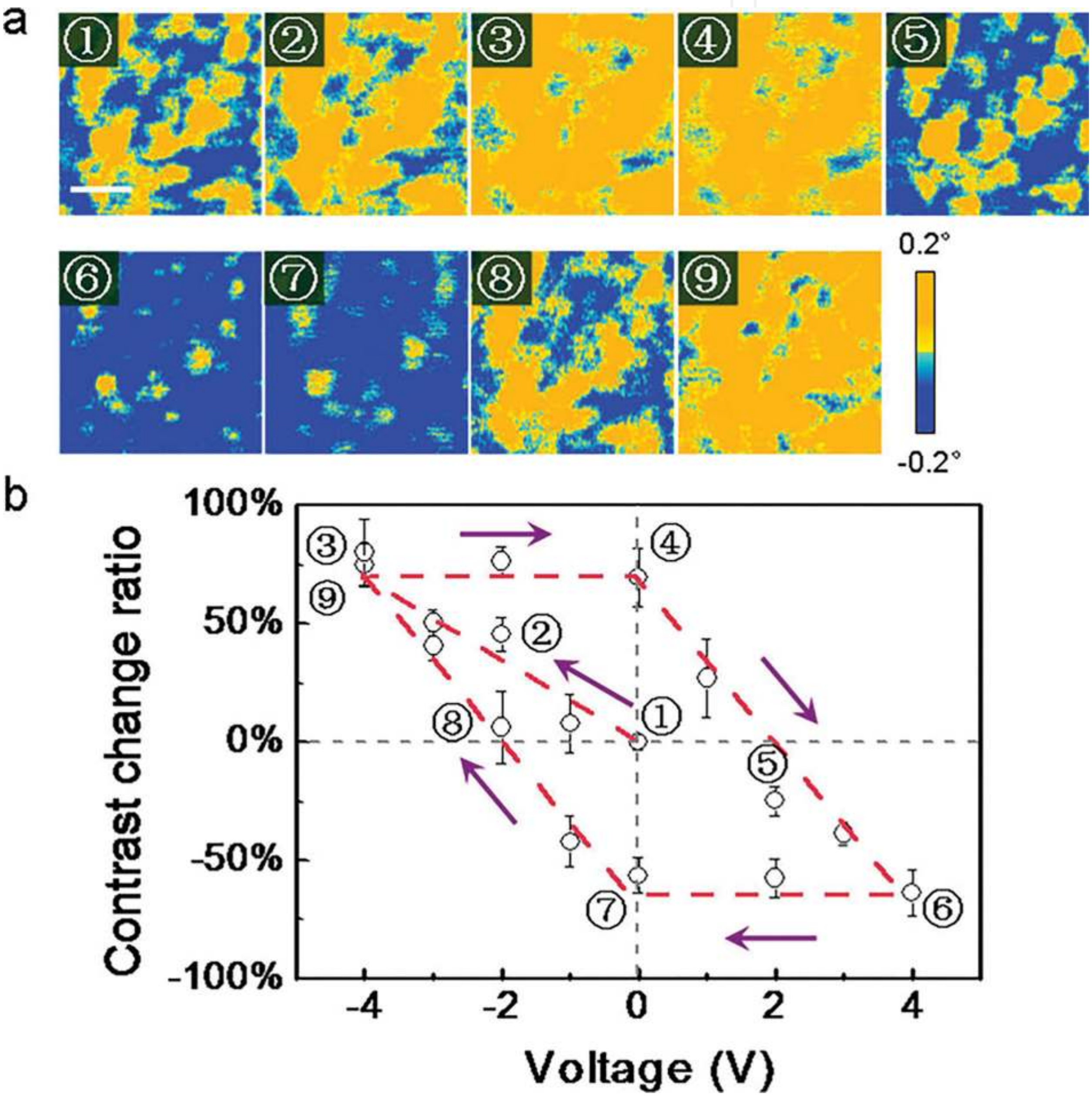


Figure 17. Electric field-controlled magnetization reversal. (a) Magnetic force microscope (MFM) images of the CFO at initial states and after voltage bias. (b) Evolution of the contrast change ratio after being subjected to various biased voltages. Reproduced with permission from Ref. [95]. Copyright 2015 American Chemical Society.

With the electric field-induced ion migration method, our group also achieved nanoscale magnetization reversal in cobalt ferrite (CFO) thin film (**Figure 17**) [95, 96]. The electric field-induced migration and redistribution of Co^{2+} between Fe vacancies induced the unidirectional magnetic anisotropy of the sample along the <110> directions. The reported magnetization reversal is nonvolatile and reversible, which can be controlled by tuning the electric field polarity and amplitude. Such a nanoscale magnetization modulation by nanoionics may provide a novel approach to manipulate the magnetization of magnetic materials for low-power magnetic memory and spintronics.

6. Challenges and possible approaches

Thanks to the efforts of scientific researchers and engineers from all over the world, the optoelectronic resistive switching has achieved great progress. However, there are still some challenges in the way of further development of optoelectronic memristors currently as follows:

1. Mechanism: the widely accepted mechanism of PPC is the photo-induced charge trapping and detrapping in defects. However, due to the technique limitation of directly mapping photo-generated carriers' distribution under light illumination, it is hard to clarify the PPC at electron scale.
2. Materials and performances: many materials are photoresponsive and resistance switchable. Therefore, finding a durable, reliable, and CMOS-compatible material with excellent optoelectronic resistive switching performances is still a challenge, and the performance especially the speed is more challenge due to defects-related process.
3. Spatial design of the optoelectronic neural networks: optoelectronic platform will need to integrate light source to the integrated circuits. Therefore, the devices' surface and physical position should be accessible for light source. Then the best way to route the light source to devices' surface is a critical issue.

Possible approaches include the following:

1. Mechanism: light-integrated TEM is a possible method to observe the light-controlled physical properties. In my current group in Finland, an *in situ* TEM under external electric field and light sources is ready, and there may be some promising results about optoelectronics in the following years [97].
2. Materials and performance: the direct and effective way to find a suitable material is trying and trying. One promising material has to be tested, optimized, and improved repeatedly before the product, and what we can do is to just be patient. The performance requirement depends on the application, so performance is negotiable [17].
3. Spatial design of the optoelectronic neural networks: with the development of nanophotonics and nanolasers, in the near future, integrated photonics will provide efficient and feasible approach to address the spatial design of optoelectronic artificial neural networks [6].

7. Conclusions and prospects

In this chapter, recent progress on optoelectronic resistive switching are introduced and summarized. Due to the photosensitive media in memristor, light can be used as another degree of freedom to control the resistive switching behavior for multifunctional optoelectronic devices. Here, the main mechanism is the photo-induced carriers trapping and de-trapping in defects in the semiconductor "memory" layer. To further promote the development of the multifunctional optoelectronic devices, their performance should be improved to meet different applications considering image sensor, memory, logic, and neuromorphic devices.

Optoelectronic memristor-based neuromorphic devices, integrating the functions of information storage, processing, image detection, and memory together, may provide high potential for intelligent image sensor and optoelectronic in-memory computation. Based on the integrated photonics [1–10], optoelectronics [47–60], and optogenetics [98–100], an optoelectronic artificial neural network may play a key role in future human-machine interactive devices.

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Conflict of interest

The authors declare no conflict of interest.

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