Proceedings of the 2nd International Conference on Functional Materials and Civil Engineering
DOI: 10.54254/2755-2721/72/20241064

The current status of the development of photomemoryristors in the field of neuromorphic vision

Kaiyang Wang

Dalian University of Technology, Panjin, Liaoning, 124221, China

1242495011@mail.dlut.edu.cn

Abstract. As a new type of device, photoelectric memristors have the potential to mimic the human visual system. Researchers have been able to realize image enhancement, noise reduction, recognition and classification functions through optoelectronic modulation, which has a wide range of applications in the fields of neuromorphic computing and image processing. This paper discusses and analyzes the overview of amnesia, the research progress of photoelectric amnesia, as well as the application and prospect of photoelectric amnesia in artificial vision systems. Through the discussion, this paper concludes that photoelectric memristors have important application potentials in visual perception and recognition, intelligent surveillance systems, and medical image analysis. Photoelectric memristors can simulate part of the functions of the human visual system, provide more efficient and accurate image processing solutions, and are expected to bring technological breakthroughs in a number of application areas. By improving the accuracy and efficiency of image recognition and categorization, it can promote the development of intelligent systems. This is not only an important impetus for basic scientific research, but also has a profound impact on practical applications and industrial development. The prospect of wide application of photoelectric memristor means that it has the potential to become a core component of the next generation of intelligent systems, which will drive the progress and change of the whole field of science and technology.

Keywords: memristor, photoelectric memristor, neuromorphic visual system.

1. Introduction

The biological visual system is a complex system in animals, consisting of the eyes, the brain and the associated neural network. This system is well known for its ability to perceive and understand its surroundings, not only to recognize objects easily, but also to obtain information even when the environment it interprets is complex. Artificial vision systems have been a hot topic in research and development for many years, and efforts have been made to apply them to various fields such as medicine, industry, and transportation. These applications include computer vision, robotics, and medical imaging. In the field of artificial intelligence, deep learning models are inspired by biological vision systems, especially the structure of convolutional neural networks (CNNs), which have similarities with the cortical processing mechanism in animal vision systems. Deep learning models achieve excellent performance in tasks such as image recognition and object detection by learning a large amount of data and performing information processing and feature extraction through multilayer

DOI: 10.54254/2755-2721/72/20241064

neural networks, and nowadays, researchers have developed a number of neuromorphic devices to realize various artificial synapses [1-3] and neurons [4-6].

The traditional artificial vision system is composed of photoreceptors, storage units and computation units, and its main components are image sensors, image processing units, data processing and analysis units, etc. However, this architecture has significant drawbacks: the photoreceptors generate a large amount of complex data, which is not conducive to storage and computation, and increases the energy consumption burden. However, this architecture has significant drawbacks: the photoreceptor generates a large amount of complex data, which is unfavorable for storage and computation and increases the burden of energy consumption; moreover, data storage and computation are carried out separately, which leads to the inefficiency of the overall system. Neuromorphic computing, by simulating the structure and function of the brain, can significantly reduce energy consumption through a high degree of parallelism and adaptability. Compared with conventional computers, such systems typically use less power because they can process information in parallel without the need to frequently read and write to memory. In addition, neuromorphic computing systems can be used to simulate and study complex biological processes, providing new tools and methods for neuroscience research and helping to understand the workings of the brain. These features make neuromorphic computing promising for applications in many fields, including but not limited to artificial intelligence, robotics, healthcare, and the development of new computing devices. Amnesia was first proposed by Leon Chua [7], an expert in circuit theory, in 1971, and in 2008, Stanley Williams' team at Hewlett-Packard Labs [8] successfully fabricated the Pt/TiO_2/Pt structure of amnesia for the first time.

In recent years, due to its integration of storage and computation, simple structure, fast read/write speed, low power consumption and other characteristics, the memristor has become a research hotspot in the field of electronic memory devices. The resistance state of a photoelectric memristor can be changed not only by an electrical signal (voltage or current), but also can be adjusted by an optical signal (light). This optoelectronic dual control mechanism provides more manipulation means for the device, which greatly improves the efficiency of the artificial vision system. Unlike traditional image sensors, photoelectric memristors are equipped with primary image processing functions, such as noise reduction and contrast enhancement, while sensing information. Because they enable fast, low-power changes to the resistive state, photomemoryristors have potential advantages in neuromorphic computing and machine learning applications. They can mimic the behavior of biological neurons and enable brain-like computing. The ability of photoresistors to process both optical and electrical signals makes them ideal for use in optoelectronic integrated circuits. This versatility helps increase system integration and complexity while reducing power consumption and latency. Sense and Sensor: Due to their ability to respond to optical signals, photoresistors also have great potential for optical sensing and detection applications. For example, they can be used as photosensitive sensors to detect changes in ambient light intensity and convert them into electrical signals. Non-Volatile Storage: Like traditional memristors, photoresistors have non-volatile storage. This means that they retain their stored data when the power supply is disconnected.

The purpose of this paper is to comprehensively sort out the research progress of photoelectric memristors, summarize the content about the overview of memristors, and prospect the research progress of photoelectric memristors as well as the application of photoelectric memristors in artificial vision systems and their future. The research on the application of photoelectric memristors in artificial vision systems is of great theoretical and practical significance, which can help promote the development of artificial intelligence in the field of visual perception and processing, and provide new ideas and methods for the realization of smarter and more efficient artificial vision systems.

2. Overview

2.1. Definitions and Characteristics

The memristor (also known as resistance transition memory) is a new type of passive device, its resistance value can be regulated by external signals, and can memorize the resistance state, with characteristics similar to those of biological neurons. The resistance transition characteristics of the memristor are affected by the electrode material and the functional layer material. In the case of the same electrode, different functional layer materials will lead to different resistance transition behavior; and in the same functional layer materials, the use of different electrodes may also cause different resistance transition performance.

A memristor is one of the "four basic circuit elements" in circuit theory, following resistance, capacitance and inductance. The name "memristor" comes from the combination of "memory" and "resistor", and its characteristic is that it can remember the past current flow after the current has passed through it. In conventional circuit theory, there are four basic physical quantities: charge (Q), voltage (V), current (I), and magnetic flux (φ). A memristor describes the relationship between charge and magnetic flux, where ($d\varphi(q) = M(q)\, dq$), with M representing the memristor, has characteristics similar to those of a resistor. Therefore, the memristor has a charge memory function. There are many kinds of memristors, the criterion for distinguishing volatile and non-volatile is whether the conductance can be maintained after power failure; the criterion for distinguishing digital memristors and analog memristors is whether there is a clear switching threshold voltage in the process of resistance conversion.

The optical memristor is a new type of resistor, that has been widely noticed and intensively researched for its simple sandwich structure, long-term data retention, low power consumption, fast read/write speed and excellent temperature characteristics. The main features include non-volatility, rewritability, low power consumption and high response speed.

The photoelectric memristor is capable of memorizing its resistance state and remains stable even after power failure, providing powerful data storage capability. Its resistance value can be changed by external light or an electric field, thus requiring multiple rewrites and being suitable for dynamic adjustment of the resistance value. Since the photoelectric memristor is based on the physical mechanisms of photoelectric and resistive effects, it usually requires low power during its operation. In addition, the response speed of the photoelectric memristor is very fast, and the change of the resistance value can be accomplished within the microsecond level.

Photoelectric memristors utilize an optical mechanism to control the change of resistance value, which is usually realized based on the properties of photosensitive materials. Therefore, photoelectric memristors can be regarded as the application and development of memristors in the optical field.

2.2. Materials and Mechanisms

2.2.1. Functional layer materials. The functional layer of a photoelectric memristor is its core part, which is responsible for responding to and controlling optical and electrical signals. The selection of suitable functional layer materials is crucial to optimizing the performance of photoelectric memristors. Functional layer materials for memristors are usually divided into two categories: monomers and compounds. Monolithic materials such as silicon, germanium, carbon and phosphorus have demonstrated amnesic phenomena [9-11].

In terms of compounds, inorganic and organic materials have their own advantages. Inorganic materials, traditional high dielectric constant oxide materials, such as TiO_2, in ultraviolet light irradiation can produce electron-hole pairs, thus changing the resistance value, has been proven to achieve good performance in the memristor [12-18]. In terms of organic materials, polyaniline is a conductive polymer that can change its conductivity under light exposure, which is suitable for optoelectronic storage and sensor devices; polyfluorene polymers exhibit obvious changes in electrical properties under light exposure, which can be used to construct sensitive photoelectric memristors.

Researchers hope to extract specific substances from nature for the preparation of new electronic devices, in order to obtain biocompatible, environmentally friendly and low-cost electronic devices. For example, natural substances such as silk proteins and DNA are considered to have potential applications. This choice of materials based on natural substances will not only help to improve the biocompatibility of the devices, but also reduce the production cost and environmental impact, thus promoting the application of amnesia in biomedical and environmental monitoring fields.

DOI: 10.54254/2755-2721/72/20241064

2.2.2. Photon-electron coupled devices. Existing photon-electron coupling type memristor systems mainly include oxide materials [19], organic-inorganic hybridized chalcogenides [20], silicon-based materials [21], and two-dimensional materials [22]. The oxygen-sustained photoconductivity effect is a common photon-electron coupling photoelectric memristor model. As shown in Figure 1, Li's group at the Ningbo Institute of Materials Research, Chinese Academy of Sciences (CAS) utilized cerium oxide material to construct a photogated nonvolatile memristor [23]. The device structure is ITO/CeO_2 -x/AlOy/Al, in which the alumina layer is formed by spontaneous oxidation of the aluminum electrode. Due to the Fermi energy level difference between cerium oxide material and alumina, Schottky barriers are formed at the interface.

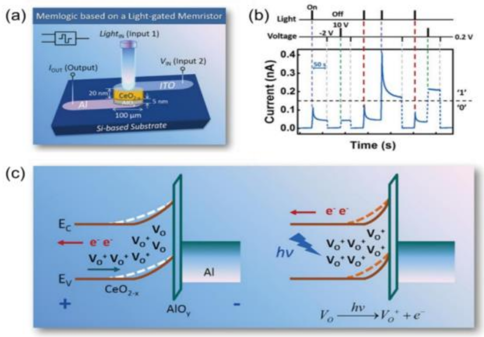

Figure 1. Cerium oxide photoelectric memristor (a) Schematic structure; (b) Light-on-electrical off behavior; (c) Schematic of the resistive mechanism [23].

2.2.3. Photon-ion coupled devices. Photon-ion coupled devices mainly realize the conductivity state transition by modulating the relevant ion kinetic processes inside the device through the light illumination process. Chai's group at the Hong Kong Polytechnic University utilized the photovariation process of molybdenum ions in molybdenum oxide to construct photoresistive variable memories [24]. The photoresist mechanism of the device is shown in Figure 2, where photogenerated holes react with adsorbed water molecules to form protons under UV irradiation. The photogenerated electrons and protons will transform the hexavalent molybdenum ions into n-pentavalent hydrogen molybdenum bronze (HyMoOx), and the device transforms from a high-resistive state to a low-resistive state; in the process of the electric shutdown, the electric field drives the protons to migrate towards the top electrode and gradually separate from the molybdenum oxide layer. The molybdenum ions return to n-valent from n-pentavalent to n-six-valent, and the device restores to a high-resistive state.

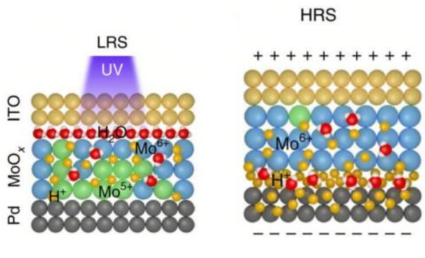

Figure 2. Diagram of the resistive change mechanism in ITO/MoOx/Pd devices [24]

3. Optical Memristors in Neuromorphic Visual Systems

3.1. Status

The human visual system [25] consists of two main components: the visual organs and the visual cortex of the brain. The visual organ is responsible for receiving and processing the external visual information, while the visual cortex of the brain further processes and interprets the information to fulfill the perceptual tasks. Similarly, photoreceptors have similar photoreceptor properties and photomodulation

DOI: 10.54254/2755-2721/72/20241064

capabilities, and can mimic some of the functions of the retina, such as image enhancement and noise reduction. By using photo-memristors as synaptic devices to build neuromorphic networks, it is possible to realize some functions similar to those in the visual cortex of the brain, such as image recognition and classification.

In 2022, Yan's team [26] designed a multifunctional artificial vision system based on Sb_2Se_3/CdS(SC) core-shell structured nanorod arrays of optoelectronic hybrid modulated memristors. The system consists of three components: the SC photoelectric memristor (simulating the human eye function), the threshold switching memristor based on Ag/MoS_2 nanosheets/Ag/MoO_x /Ag (simulating the human brain function), and the actuator (simulating the human eye muscle function). The actuator requires 12V to drive, so a voltage regulation module was attached. The amplitude of the output pulse voltage of the threshold switching memristor can be adjusted by changing the light intensity of the SC memristor. When the light intensity is low, the system only stores the image; when the light intensity is high, the output voltage exceeds the set range and drives the actuator to close the mechanical eye, simulating the self-protection function of the human eye by closing the eye when stimulated by bright light.

Photomemoryristors can realize the neuromorphic computation function of traditional electrical devices and respond to optical signals directly, thus realizing the integration of sensory storage and computation functions, which is an ideal hardware choice for the construction of new neuromorphic visual systems. At present, the research on the neuromorphic visual function of photoelectric memristors has achieved a stage of progress.

3.1.1. Boolean logic arithmetic functions. Compared with electrical signals, optical signals have the unique advantages of low power consumption, high bandwidth and low crosstalk, which are suitable for the development of optoelectronic logic operations. Chen's research group at Fudan University used zinc oxide material to construct an optically-enhanced electrically suppressed memristor device, which successfully realized the function of reconfigurable Boolean logic operation [27]. As shown in Figure 3(a), the optical signal and positive electric pulse are used as the optical and electrical input signals respectively, and the negative electric pulse is used as the modulation signal; the current state of the device is used as the logic output. Based on this, the array-level operation can be realized, as shown in Figure 3(b).

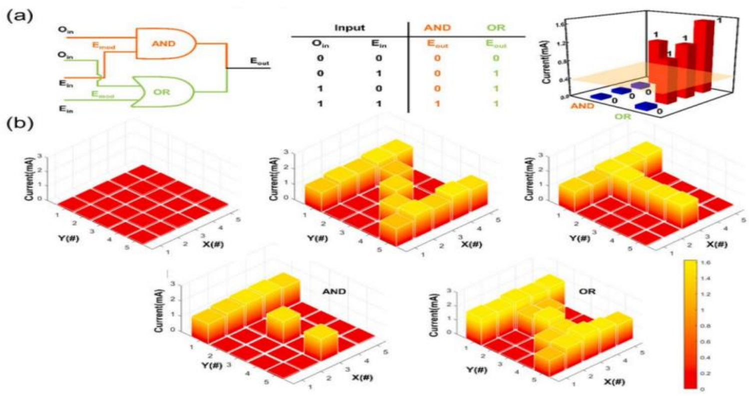

Figure 3. (a) Reconfigurable logic operation function; (b) Image logic operation based on 5 × 5 photomemory arrays [27].

3.1.2. Image pre-processing functions. Chai's group at the Hong Kong Polytechnic University used molybdenum oxide to construct a novel photoresistive variable random memory and realized neuromorphic visual sensing function [24]. As shown in Figure 4, the research group constructed an 8×8 photoresistor array and completed a simple image sensing storage process. Increasing the light intensity can significantly improve the storage effect of image information. In addition, the nonlinear response of the device to different intensity light signals can realize the image preprocessing function, and the main

DOI: 10.54254/2755-2721/72/20241064

features of the image information are enhanced. The final pattern recognition process shows that the preprocessing process can significantly improve the overall recognition accuracy and recognition rate.

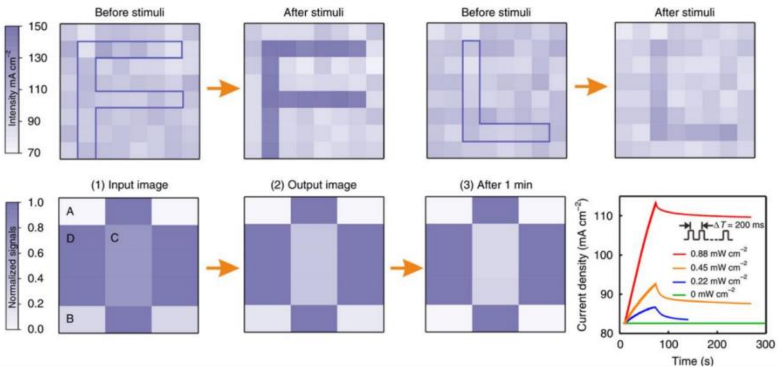

Figure 4. Image preprocessing function based on molybdenum oxide photomemory arrays [24]

3.2. Areas of application

3.2.1. Visual Perception and Recognition. Optical amnesia can be used to simulate the perception and recognition processes in the human visual system. By simulating the function of synapses, the neuromorphic visual system can learn and recognize different visual patterns and image features. Photoreceptors play an important role in object recognition. By training the neuromorphic visual system, the photomemory can help the system learn the features of different objects, including shape, color, texture, and so on. These features are stored in the neural network simulated by the photomemoryristor, which enables the system to quickly and accurately match and recognize objects in new images, thus achieving efficient object recognition. This application is particularly important in the fields of self-driving cars and intelligent security systems. In self-driving cars, photoelectric memristors can help the system identify vehicles, pedestrians, traffic signs and road conditions in real time, thus assisting the vehicle to make accurate driving decisions. In an intelligent security system, the rapid recognition ability of photoelectric memory can help the system classify and respond to different objects and scenes in real time, so as to improve the accuracy and efficiency of the monitoring system. In the field of face recognition, photo memristors also have great potential. By mimicking the neural network that processes facial information in the human brain, PVM can help the system learn and memorize the unique features of different faces, such as eye spacing, face shape and skin color. This ability makes photoelectric amnesia play an important role in the field of face recognition, not only accurately identify the face, but also further analyze the facial expression and determine the emotional state. This application prospect is very wide in the fields of security monitoring, human-computer interaction and social media. In security monitoring, photoelectric memristors can help the system recognize and track specific faces in real time, thus improving the security and accuracy of the monitoring system.

3.2.2. Intelligent Monitoring System. Photomemoryristors have a wide range of applications in neuromorphic vision systems, especially in building intelligent surveillance systems. By simulating synaptic connections, PAMs enable the system to learn and recognize various actions, postures and behaviors, thus realizing real-time monitoring and alerting functions for these behaviors. In the field of security monitoring, photoelectric memristors show significant advantages, which can help the monitoring system, accurately identify a variety of unusual or suspicious movements and behaviors in real time. For example, when someone tries to climb a fence, break into a restricted area, or carry a suspected dangerous object, the system can quickly detect these abnormalities through the high efficiency of the photoelectric memristor processing power and immediately issue an alarm. At the same time, the system can also automatically take corresponding measures according to the preset security policy, such as locking the door, notifying security personnel or triggering other emergency response

DOI: 10.54254/2755-2721/72/20241064

mechanisms. This real-time monitoring and rapid response capability, for the protection of public places, to ensure the normal operation of important facilities and to maintain the safety of personal property, plays a vital role. In the field of traffic monitoring, the application of photoelectric memristors has also revolutionized traffic management. Photoelectric memristors can efficiently identify a variety of traffic violations, such as running red lights, driving against traffic, speeding, etc. They can instantly capture these traffic violations. They can instantly capture these violations and pass the information to the traffic management system for real-time processing. In this way, the traffic management department can more effectively monitor the road conditions, detect and deal with violations in a timely manner, thus improving the overall traffic safety level and traffic efficiency.

3.2.3. Medical Image Analysis. The application of photomemoryristors in neuromorphic visual systems, especially in the analysis and diagnosis of medical images, shows great potential. By mimicking the workings of neurons in the brain, photomemoryristors can efficiently process and learn from a large amount of medical image data to recognize different lesion patterns and structural features. For example, when processing a wide range of medical images such as X-rays, magnetic resonance imaging (MRI) scans, and computed tomography (CT) images, PDAs can identify small but significant abnormal changes, such as early signs of tumors, abnormal dilatation or constriction of blood vessels, and diseased areas of tissues. This technology can also significantly improve the accuracy and efficiency of pathology analysis. In traditional methods, pathologists usually need to spend a lot of time and effort on microscopic observation and analysis of samples. With the help of photomemory, the neuromorphic vision system can automatically process and analyze the images of pathology slides and quickly identify potential diseased cells and tissues. This not only speeds up the diagnostic process, but also reduces the possibility of human error and improves overall diagnostic accuracy.

4. Outlook

As a new type of device, the photoelectric memristor has the potential to play an important role in intelligent sensing systems, neuromorphic computing, Internet of Things devices and other fields. Currently, the research and development of photoelectric memristors are in a progressive stage. In the field of scientific research, the cooperation between academia and industry promotes the continuous innovation of photoelectric memristors, including the exploration of new materials, the optimization of device structure, the improvement of the fabrication process, etc. In practical applications, the photoelectric memristors can be used in a variety of applications. In terms of practical applications, photoelectric memristors have gradually demonstrated their application potential in some fields, such as smart sensors, neuromorphic computing chips, optical storage devices, etc. Moreover, photoelectric memristors have been used in a variety of applications, including the development of new materials, optimization of device structure, and improvement of manufacturing processes. However, photoelectric memristors still face some challenges, such as the complexity of the fabrication process, the stability of the device, the lack of integration performance and other issues, which limit their further development in commercial applications.

Photoelectric memristors have a broad development prospect in artificial vision systems. With the continuous development of artificial intelligence and machine vision technology, the photoelectric memristor, as a new type of device, has important application potential. Firstly, a photoelectric memristor can realize the integration of photoelectric conversion and storage functions, which can realize more efficient data processing and storage in an artificial vision system. Secondly, photoelectric memristors have non-volatile storage characteristics, that can keep the data in the event of power failure, which is conducive to the realization of low-power, fast-starting intelligent vision systems. In addition, photoelectric amnesia also has a high degree of integrability and flexibility, can realize multi-functional vision processing, including image recognition, pattern matching, target tracking and other applications. In the future, photoelectric memristors are expected to play an important role in the fields of intelligent surveillance, automatic driving, intelligent robotics, etc., providing new technical means and solutions for the development of artificial vision systems. However, in order to realize this prospect, it is still

DOI: 10.54254/2755-2721/72/20241064

necessary to overcome the complexity of the manufacturing process of photoelectric memristors, stability and other challenges, and continue to promote its technological progress and commercialization.

5. Conclusion

The photoelectric memristor can simulate some key functions of the human visual system, such as image enhancement, noise reduction, recognition and classification. Through its optoelectronic modulation, the photoreceptor can directly respond to optical signals and realize the integration of sensing, storage and computation. In this paper, the development status of photoelectric memristors in the field of neuromorphic vision is summarized. Photoelectric memristors are not only able to dynamically adjust the resistor value according to the electrical signal like traditional memristors, but also respond to the optical signal, which has the advantages of low power consumption and high-density integration, and, at the same time, can improve the efficiency of data processing and storage. Photoelectric memristors are excellent at simulating biological synaptic behavior and are suitable for building efficient neural networks and artificial intelligence systems. They can realize fast learning and memory processes and facilitate the development of brain-like computing.

Combined with optoelectronic properties, photoelectric memristors show great potential in the fields of optical computing and information processing, and can be used in optical communication and image processing systems to realize faster and more efficient information processing and transmission. Currently, the research on photoelectric memristors is still in the development stage, and the improvement of material selection and fabrication processes is the key. The application of nanomaterials and two-dimensional materials (e.g. graphene, molybdenum disulfide, etc.) is expected to further improve the performance and stability of the devices. Although the photoelectric memristor shows broad application prospects, in visual perception and recognition, intelligent surveillance systems and medical image analysis have important application potential, its consistency, durability and manufacturing costs are still facing challenges; its commercialization is still faced with the complexity of the manufacturing process, device stability and integration of performance are insufficient and other issues. Future research should be devoted to solving the above technical problems and exploring new material and structure design, in order to promote the wide application of photoelectric memristors in the fields of intelligent sensors and neuromorphic computing chips, etc. In conclusion, photoelectric memristors have the potential to be used in a wide range of applications. In conclusion, as a kind of cutting-edge electronic device, the photoelectric memristor, which combines optical and electrical characteristics, has important application value in the next generation of computing and storage technology. With the deepening of research and technological progress, photoelectric memristors are expected to realize breakthroughs in many fields and promote the innovation of information technology and electronic engineering.

References

[1] Llinas R., Steinberg I. Z., Walton K. Relationship between presynaptic calcium current and postsynaptic potential in squid giant synapse [J]. Biophysical Journal, 1981, 33(3): 323-351.
[2] Elgersma Y., Silva A. J. Molecular mechanism of synaptic plasticity and memory [J]. Current Opinion in Neurobiology, 1999, 9(2): 209-213.
[3] Zidan M. A., Strachan J. P., Lu W. D. The future of electronics based on memristive systems [J]. Nature Electronics, 2018, 1(1): 22-29.
[4] Prezioso M., Merrikh-Bayat F., Hoskins B. D., et al. Training and operation of an integrated neuromorphic network based on metal-oxide memristors [J]. Nature, 2015, 521(7550): 61-64.
[5] Wang Z., Joshi S., Savel'ev S. E., et al. Memristors with diffusive dynamics as synaptic emulators for neuromorphic computing [J]. Nature Materials, 2017, 16(1): 101-108.
[6] Jo S. H., Chang T., Ebong I., et al. Nanoscale memristor device as synapse in neuromorphic Systems [J]. Nano Letters, 2010, 10(4): 1297-1301.
[7] Adhikari S. P., Sah M. P., Kim H., et al. Three fingerprints of memristor [J]. IEEE Transactions on Circuits and Systems I: Regular Papers, 2013, 60(11): 3008-3021.

DOI: 10.54254/2755-2721/72/20241064

[8] Liu S., Sun Y., Song B., et al. Understanding the conduction and switching mechanism of Ti/AlOx/TaOx/Pt analog memristor [J]. Physics Letters A, 2019, 383(30): 125877.

[9] Gorshkov O., Filatov D., Koveshnikov S., et al. Bipolar resistive switching in memristors based on Ge/Si(001) epitaxial layers [J]. Journal of Physics: Conference Series, 2020, 1695(1), 012158.

[10] Rehman S., Khan M. F., Aftab S., et al. Thickness-dependent resistive switching in black phosphorus CBRAM [J]. Journal of Materials Chemistry C, 2019, 7(3): 725-732.

[11] Yan X., Zhao J., Liu S., et al. Memristor with Ag-cluster-doped TiO_2 films as artificial synapse forneuroinspired computing [J]. Advanced Functional Materials, 2018, 28(1): 1705320.

[12] Li Y., Tang J., Gao B., et al. High - uniformity threshold switching HfO_2 - based selectors with patterned Ag nanodots [J]. Advanced Science, 2020, 7(22): 2002251.

[13] Banerjee W., Zhang X., Luo Q., et al. Design of CMOS compatible, high-speed, highly-stable complementary switching with multilevel operation in 3d vertically stacked novel HfO_2/Al_2O_3 /TiOx (HAT) RRAM [J]. Advanced Electronic Materials, 2018, 4(2): 1700561.

[14] Park G.S., Kim Y. B., Park S. Y., et al. In situ observation of filamentary conducting channels in an asymmetric Ta_2O_5 −x/TaO_2 −x bilayer structure [J]. Nature Communications, 2013, 4(1), 2382.

[15] Fu Y., Zhou Y., Huang X., et al. Reconfigurable synaptic and neuronal functions in a V/VOx /HfWOx /Pt memristor for nonpolar spiking convolutional neural network [J]. Advanced Functional Materials, 2022, 32(23), 2111996.

[16] Yoong H. Y., Wu H., Zhao J., et al. Epitaxial ferroelectric $Hf_{0.5}Zr_{0.5}O_2$ thin films and their implementations in memristors for brain - inspired computing [J]. Advanced Functional Materials, 2018, 28(50): 1806037.

[17] Yang Y., Gao P., Li L., et al. Electrochemical dynamics of nanoscale metallic inclusions in dielectrics [J]. Nature Communications, 2014, 5(1), 4232.

[18] Goswami S., Matula A. J., Rath S. P., et al. Robust resistive memory devices using solution-processable metal-coordinated azo aromatics [J]. Nature Materials, 2017, 16(12), 1216-1224.

[19] Kumar N., Patel M., Nguyen T. T., et al. All-oxide-based and metallic electrode-free artificial synapses for transparent neuromorphic computing [J]. Materials Today Chemistry, 2022, 23:100681.

[20] Li Y., Cheng P., Zhou L., et al. Light-induced nonvolatile resistive switching in $Cs_{0.15}FA_{0.85}PbI_3$-XBrX perovskite-based memristors [J]. Solid-State Electronics, 2021, 186: 108166.

[21] Wang J., Ilyas N., Li C, et al. Enhanced broadband Si-based optoelectronic synapse for artificial visual applications [J]. Applied Surface Science, 2023, 614: 156232.

[22] Kwon K. C., Baek J. H., Hong K, et al. Memristive devices based on two-dimensional transition metal chalcogenides for neuromorphic computing [J]. Nano-Micro Letters, 2022, 14(1): 58.

[23] Tan H., Liu G., Yang H., et al. Light-gated memristor with integrated logic and memory functions [J]. ACS nano, 2017, 11(11): 11298-11305.

[24] Zhou F., Zhou Z., Chen J., et al. Optoelectronic resistive random access memory for neuromorphic vision sensors [J]. Nature nanotechnology, 2019, 14(8):776-782.

[25] Shepherd R. K., Shivdasani M. N., Nayagam D. A. X., et al..Trends in Biotechnology [J] 2013, 31(10): 562-571.

[26] Pei Y. F., Li Z. Q., Li B., et al. Advanced Functional Materials [J]. Physics Letters B, 2022, 32(29): 2203454.

[27] Wang T. Y., Meng J. L., Li Q. X., et al. Reconfigurable optoelectronic memristor for in-sensor computing applications [J]. Nano Energy, 2021, 89:106291.