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PERSPECTIVE

Novel retina-like optoelectronic sensors based on two-dimensional nanomaterials

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Artificial intelligence technology is continuously advancing, with intelligent perception playing a crucial role. While corresponding sensing technologies have made significant progress, the information acquired by sensors from external sources remains insufficient, especially when compared to the human retina's information-processing capabilities. Additionally, the physical separation of sensing elements and processing units leads to redundant hardware, which is far less integrated than the human sensing systems. Therefore, bionic perceptual systems inspired by human sensory mechanisms hold great potential for advancement. This article provides a brief overview of four retina-like optoelectronic sensors, each utilizing different optoelectronic coupling mechanisms. These sensors mimic the human retina from the perspectives of device structure, energy consumption, integration, and responsiveness. Finally, we discuss the future prospects and advancements of bionic sensing systems based on retinal-like photosensors.

INTRODUCTION

Entering the 21st century, artificial intelligence (AI) technology has entered a phase of rapid growth, with the potential to propel humanity into the fourth industrial revolution.[1,2] Intelligent perception, a key component of AI, enables machines to mimic human perceptual abilities through various sensors, allowing them to sense, understand, and respond to the external environment.[3] However, traditional sensors' limited information can no longer meet the demands for acquiring multiple information modes in the intelligent age.[4] Moreover, large amounts of data are generated at sensing nodes, processed in the computing units, and stored in memory, with physically separated functional units causing high power consumption and high latency.[5] The human perception system, with its unique structure and processing capability, offers much higher integration and efficiency than the current machine perception system.[6] Inspired by human perception systems, bionic perception systems with high responsiveness, low power consumption, and multimodality present considerable potential in the field of intelligent perception.[7] Against this backdrop, retina-like optoelectronic sensors have garnered increasing attention, as they can emulate both the structure and function of the human retina to enable low-energy, high-efficiency information acquisition. This article primarily focuses on the fundamental principles, typical examples, and scientific discussions surrounding four types of retinal-like optoelectronic sensors.

FUNDAMENTALS OF THE PHOTOELECTRIC COUPLING MECHANISM

When a beam of light with photon energy greater than the semiconductor's forbidden bandgap (E_g) irradiates the surface of the semiconductor, intrinsic and impurity absorption occurs, generating excess carriers in the semiconductor. This process increases the semiconductor's conductivity, thereby enabling the conversion of light into electrical energy. Devices based on this photoelectric coupling mechanism are known as photoelectric sensors. Recent studies have shown that some of these sensors can mimic the plasticity of biological synapses,[8] while others have energy consumption comparable to that of biological neurons.[9] Additionally, some exhibit multimodality for multifunctional integration,[10] and others can mimic the light-dark recognition behavior of the human visual system.[11] These sensors, which replicate various functions of the human retina, are referred to as retina-like photoelectric sensors. Different two-dimensional (2D) materials exhibit distinct carrier generation characteristics under the photoelectric coupling mechanism, which can be categorized as follows: 1) 2D materials capable of generating nonvolatile carriers, showing different transient properties under the same power and varying wavelengths of light excitation, suitable for artificial optical synapses; 2) 2D materials with high responsivity and low energy consumption, suitable for phototransistor; 3) 2D materials with multimodal input properties, suitable for multifunctional integrated optical sensing arrays.

ARTIFICIAL OPTICAL SYNAPSES

The human retina relies on synapses and neurons to transmit information, with neurons depending on synapses for connectivity and signaling. Synaptic plasticity, the basis of learning and memory in the human brain, plays an important role in enabling the advanced functions of the biological nervous system. Similarly, optoelectronic synaptic devices mainly rely on optical signals or combined optoelectronic signals to implement synaptic function simulation, and the synapse's weight is represented by the device's conductance or resistance. Jie Gong *et. al.* have integrated an asymmetric 2D MoS_2/CIPS ferroelectric heterostructure field-effect transistor (AFe-FET) with an integrated triboelectric nanogenerator (TENG) to create an artificial optical neural device (Figure 1A & B).[8] Typical synaptic behaviors, such as excitatory postsynaptic current (EPSC) (Figure 1C), paired-pulse facilitation (PPF), short-term memory (STM), and long-time memory (LTM), were successfully simulated. Furthermore, the excellent photosensitivity of MoS_2/CIPS heterojunction allows light to trigger the postsynaptic current and update the synaptic weights, enriching the diversity of synergistic synaptic functions.

PHOTOTRANSISTOR

Phototransistors are functional crystals that convert light into electrical energy, and altering their materials and structure can reduce energy consumption even to the level of biological synapses. Guangcheng Wu *et. al.* have designed an α-phase indium selenide (α-In_2Se_3) phototransistor (Figure 1D & E).[9] As a 2D ferroelectric semiconductor of channel material, this phototransistor was used to construct artificial optical and electrical synapses, enabling advanced in-sensor processing (PIS) and in-memory computation (CIM) capabilities. As an optical neural synapse for low-level sensory processing, the α-In_2Se_3 phototransistor exhibits excellent photoresponsivity (2855 A/W) and detectivity (2.91×10^{14} Jones), which facilitates efficient feature extraction. For advanced processing tasks at electrical synapses, it offers a fast programming/erasing speed of 40 ns (Figure 1F) and ultra-low energy consumption of 0.37 aJ/pulse (Figure 1G). This work successfully demonstrated an AI vision system using α-In_2Se_3 phototransistors, achieving a remarkable 92.63% recognition accuracy over 12 cycles through the synergy of PIS and CIM functions.

MULTIMODAL OPTICAL MEMRISTOR

Human perceptual systems are much more integrated than machine perceptual systems. Meanwhile, multimodal fusion sensing in the retinal nervous system enables humans to obtain comprehensive visual information and make accurate judgments. Therefore, multimodal devices capable of processing various types of data inputs hold significant research value. Jiajia Zha *et. al.* demonstrated an electronic/optoelectronic FG memory device enabled by tellurium (Te)-based 2D van der Waals (vdW) heterostructure for multimodal reservoir computing (RC) (Figure 1H).[10] Under strong electrical pulse stimulation, the prepared devices exhibit excellent nonvolatile electronic storage properties, including fast switching speed (≈ 100 ns), high extinction ratio (≈ 10^8), long cycling (> 4000 cycles), and retention (> 4000 s) stability. More importantly, the device efficiently responds to both electrical and optical signals, allowing mixed inputs into the RC system for feature extraction

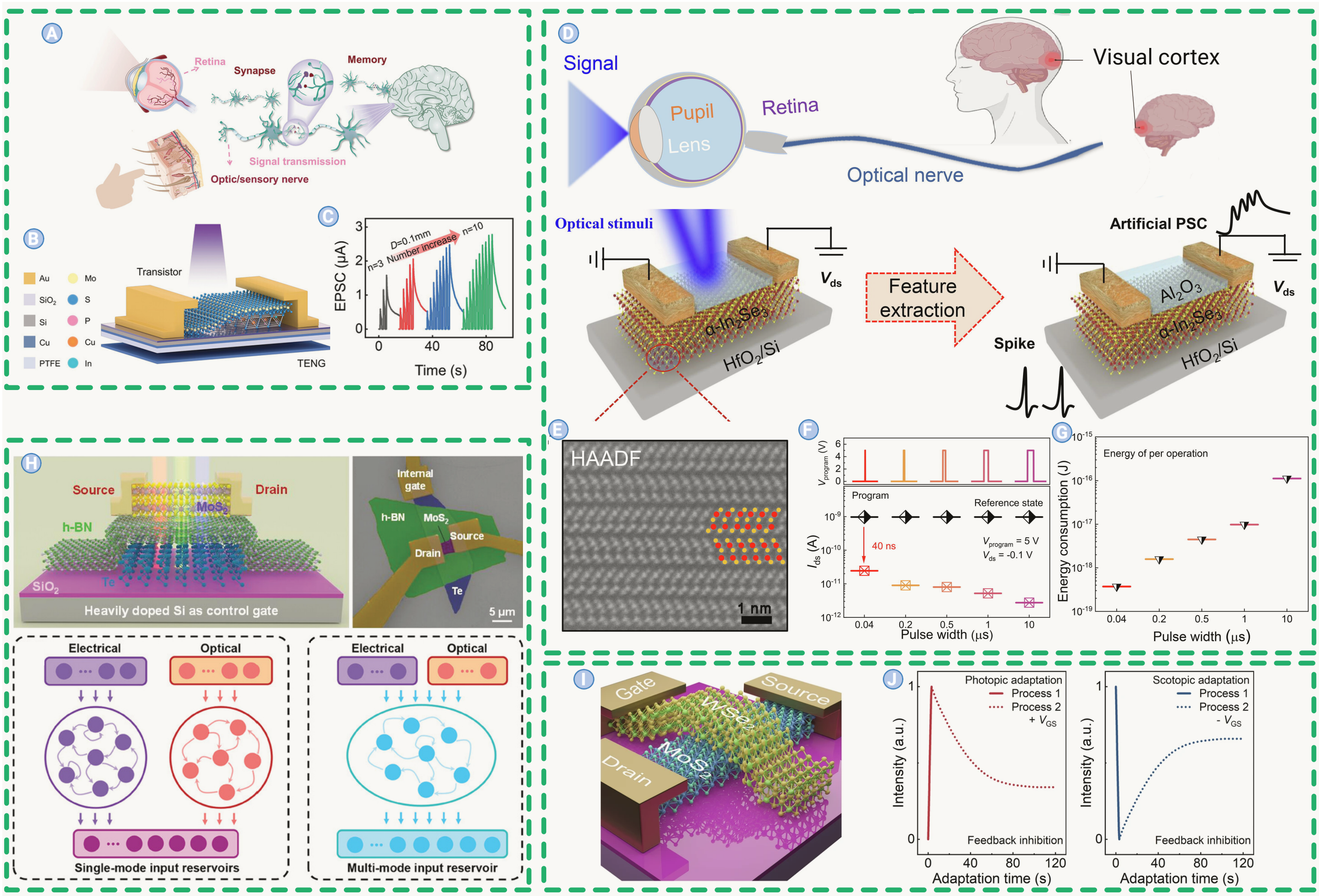

Figure 1. Device Schematic and Characterization Curves (A) Schematic diagram of the human tactile/visual sensory system. (B) 3D schematic of the artificial synapse based on asymmetric MoS_2/CIPS heterostructure. (C) Real-time excitatory postsynaptic currents (EPSC) responses. Reproduced with permission.[8] Copyright 2024, Wiley-VCH Verlag. (D) α-In_2Se_3 Fe-FET-based artificial intelligence vision system. (E) Cross-sectional high-angle annular dark-field image of α-In_2Se_3 demonstrating the 2H stacking structure. The red and yellow points indicate the In and Se atoms, respectively. (F) Program erase time of α-In_2Se_3 Fe-FET with various pulse widths. (G) Energy consumption for corresponding different pulses. Reproduced with permission.[9] Copyright 2024, Science China Press. (H) Schematic illustration of the floating gate (FG) memory device based on MoS_2/h-BN/Te heterostructure. Reproduced with permission.[10] Copyright 2024, Wiley-Blackwell. (I) Schematic diagram of the 2D $MoSe_2$ photoelectric sensor. (J) Photopic and scotopic adaptation of the device. Reproduced with permission.[11] Copyright 2024, Springer Nature.

and multi-sensor fusion. This provides an effective strategy for multimodal devices.

PHOTOELECTRIC SENSORS

The human visual system exhibits remarkable efficiency in processing visual information, which underscores the need for novel adaptive optoelectronic c-sensors to enhance speed, efficiency, and reliability.

Ling Li *et. al.* proposed a bionic 2D $MoSe_2$ photoelectric sensor for fast, high-frequency visual adaptation behavior with microsecond-level accurate perception, which adapts over 10^4 times faster than the human retina and previously reported bionic sensors (Figure 1I).[11] The photoelectric sensor switches between avalanche and photoconductive effects as the light intensity changes, varying its responsiveness in both magnitude and sign (from 7.6×10^4 to -1×10^3 A/W). This results in ultrafast defocus and photopic adaptation processes of 108 μs and 268 μs, respectively (Figure 1J). By combining a convolutional neural network with this optoelectronic sensor, adaptive machine vision is achieved, enabling excellent microsecond fast adaptation and robust image recognition with over 98% accuracy in both dim and bright conditions.

CONCLUSION AND OUTLOOK

Significant progress has been made in retinal-like optoelectronic sensors within bionic sensing systems. Artificial optical synapses exhibit biological synapse-like tunability as well as very low energy consumption, while accelerated image preprocessing effects can be observed over a wider range of wavelengths, even extending beyond the perceptual range of the human visual system. Phototransistors hold great potential for enhancing processing power in future vision hardware, improving power efficiency, and advancing artificial intelligence applications. Multimodal memristors enable artificial vision systems with multifunctional image processing, significantly increasing integration density, simplifying circuit design, and reducing fabrication and integration complexity. Photoelectric sensors are advancing the development of bionic neuromorphic chips, offering promising opportunities for future bio-inspired vision systems.

The performance of retina-like devices has far surpassed that of traditional photoelectric sensors, but there remains a big gap compared to the human retina. For example, the biocompatibility of retina-like devices could be further optimized for medical applications. Future research should focus on developing retina-like devices and their data-processing systems with lower energy consumption, faster response, and higher integration. Attention should also be given to the bipolar and polymorphic response of retina-like devices to enable the direct extraction of optical motion information. This will provide a viable path toward realizing multimodal modulation of synaptic plasticity, multifunctional sensory memory, neuromorphic devices, and bionic electronics.

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DECLARATION OF INTERESTS

The authors declare no competing interests.