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RESEARCH HIGHLIGHTS

# 2D transition metal dichalcogenides for neuromorphic vision system

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It has been a long-sought dream for human beings to realize a powerful and reliable artificial vision system that can liberate human beings from tedious brain work. In the past few years, computer vision based on brain-inspired algorithm has made great achievements in several commercial applications such as the face recognition, medical image diagnosis and driverless vehicles. Nonetheless, the mainstream computer hardware is based on the von Neumann architecture which cannot meet the growing needs for powerful and energy-efficient artificial intelligence. Fortunately, two dimensional (2D) transition metal dichalcogenides (TMDCs) device that can mimic neural architectures may allow us to overcome these challenges.

To recreate flexibility, sensitivity and adaptability in biological visual system, the exploration of emerging materials with high photoresponsivity and synaptic plasticity has become the most critical requirement for the neuromorphic devices[1–4]. The 2D TMDCs (Fig. 1(a)) not only possess an excellent optoelectronic performance but also offer an external electrical tenability for the synaptic setting. By stacking different 2D materials together, the optical response of van der Waals (vdW) heterostructures can be modulated by using the piezo-phototronic effect[5]. Compared with conventional semiconductor materials, the TMDCs-based vdW heterostructures take advantages like lightweight, semitransparency and flexibility. In addition, the fabrication technology of 2D materials has the potential to offer efficient large-scale integration due to their thermodynamic stability and interlayer coupling capability[5]. Therefore, 2D TMDCs are the ideal candidate for realizing hierarchical organizations and synaptic functions.

In 2020, Wang *et al.* proposed a neuromorphic vision system by networking a retinomorphic sensor and a memristive crossbar[4]. The sensor (Fig. 1(b)) was fabricated by using $WSe_2$/h-BN/$Al_2O_3$ van der Waals heterostructures with gate-tunable photoresponses. This device could mimic human retinal capabilities for sensing and processing images. The bulk $WSe_2$ and h-BN were processed into thin flakes by mechanical exfoliation and then transferred onto $Al_2O_3$ layer to realize vdW heterostructure. Under light illumination, the photoresponse changed with the back-gate voltage, resembling a light-stimulated biological response of the bipolar cell in retina[6]. By networking such retinomorphic sensors (Fig. 1(c)), the square array with nine nodes could perform a real-time multiplication of the projected image. The image information could be detected and pre-processed before coming into the memristive neural network for complex visual perception. Therefore, the limitation of transmission bandwidth in the conventional computer vision could be broken and the resulting high latency is minimized. This neuromorphic vision system also holds promising capabilities in carrying out object-tracking tasks.

Recently, Mennel *et al.* also demonstrated that the early processing occurring in retinomorphic sensor could drastically increase the efficiency of signal processing[1]. Similar to previous retinomorphic sensor, they presented a $WSe_2$ photodiode array that could simultaneously sense and process images projected onto the chip. The light intensity of each image pixel was multiplied with the tunable photoresponsivity of each photodiode, generating the processed output currents. Such bio-inspired pre-processing ability could greatly accelerate the image recognition and take great advantage in processing large-scale data. In this way, the photodiode array finally achieved ultrafast image recognition with a throughput of 20 million bins per second.

To realize a superior intelligence similar to human brain, the neuromorphic photoelectronics usually requires not only high photoresponsivity but also fundamental synaptic characteristics. In a recent work from Cheng *et al.*[7], the TMDCs-based heterojunction exhibited a wide variety of classical neuromorphic behaviors such as excitatory postsynaptic current (EPSC), inhibitory postsynaptic potential (IPSP), and paired-pulse facilitation (PPF). When light irradiation was applied, large numbers of electron–hole pairs were first generated in the photosensitive material $CsPbBr_3$ and then separated under the built-in electric field (Fig. 1(d)). Therefore, the light intensity could flexibly control the photoelectric performance of TMDCs devices by changing the carrier-transport characteristics at the heterojunction interfaces. In particular, the mixed-dimensional vertical van der Waals heterojunction phototransistor (MVVHT) could well mimic complex neuromorphic behaviors such as efficiency-adjustable photoelectronic Pavlovian conditioning. Fig. 1(e) schematically presented the mathematical modes of the corresponding neural algorithms. The neuronal additive operations are induced by the rate-varied electric or optic stimulus. Therefore, the neuronal in-

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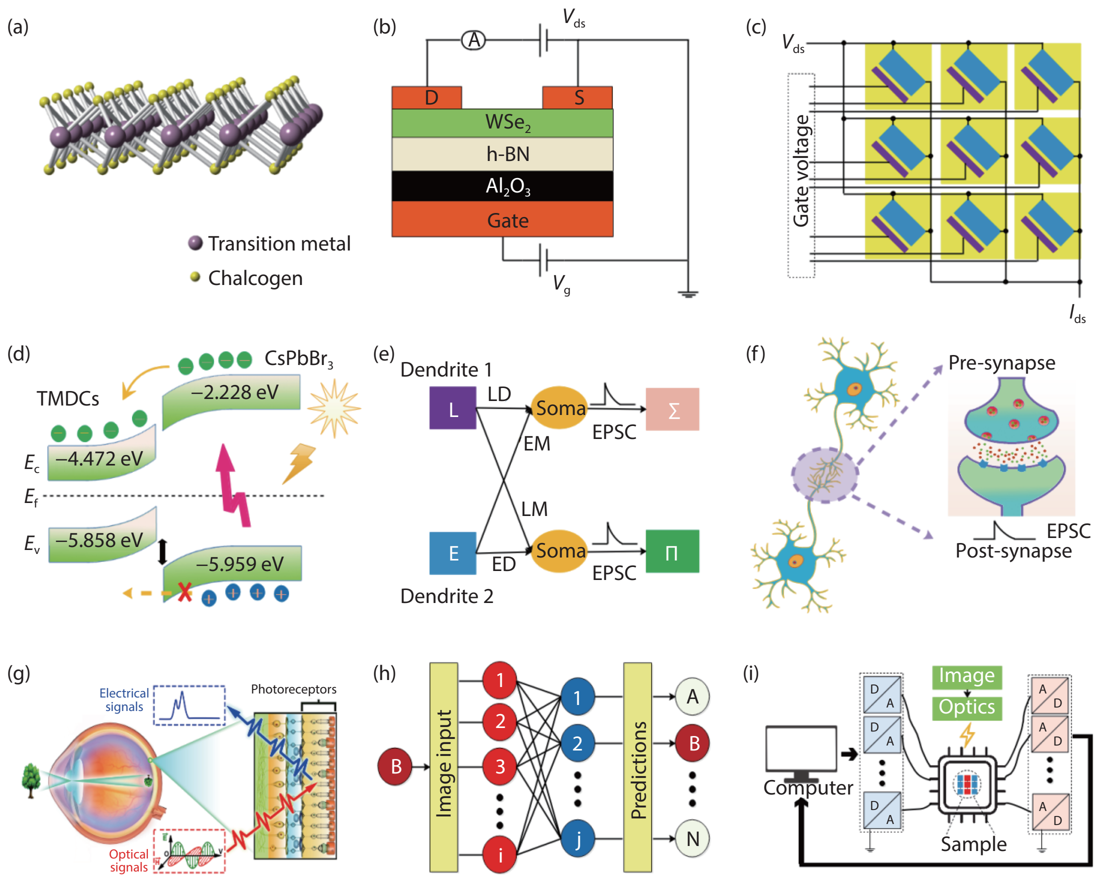


Fig. 1. (Color online) (a) Monolayer structure for transition metal dichalcogenides (TMDCs). (b) Retinomorphic sensor based on $WSe_2$/h-BN/$Al_2O_3$ vdW heterostructure. (c) Retinomorphic sensor array. (d) The energy level diagram for $CsPbBr_3$/$MoS_2$ interface under light irradiation. (e) The mathematical mode for corresponding neural algorithms. LD, photo-driving input; ED, electric-driving input; LM, photo-modulation input; EM, electric-modulation input. (f) Schematic of two adjacent neurons connected by a biological synapse. (g) Biological eye model and retina structure. Reproduced with permission[8], Copyright 2020, John Wiley and Sons. (h) Neuromorphic network for image recognition. (i) Setup for training the classifier and auto encoder.

put–output (I–O) relation can be effectively tuned by changing the strength of modulatory inputs, realizing sophisticated neuromorphic computations.

In a typical synapse, the neural signals were processed and transmitted from a pre-neuron to the dendrite of a post-neuron (Fig. 1(f)). By modulating the synaptic weights, Xie *et al.* demonstrated that the visual adaptation behaviors between the pre-neuron and post-neuron could be precisely recreated by MVVHT[8]. The typical behaviors of biological adaptation, such as accuracy, sensitivity, inactivation, and desensitization characteristics, were realized due to ionic trapping or point defects in 2D TMDC. In such a TMDC-based phototransistor, the light and gate terminals were used to transmit the neural signals from pre-neuron to post-neuron. This kind of artificial synapse could be further trained by electrical or optical stimuli and finally achieves excellent neuromorphic functions such as photo-electrically modulated dendritic integrations, and Hebbian learning rules[9, 10]. In this way, the optical sensing and processing abilities could be simultaneously realized in a single TMDC-based phototransistor.

Human vision system (Fig. 1(g)) has a strong capability to perform complex image perception. It is an efficient system in which the retina can collect and pre-process optical signals avoiding the redundant information sent to visual cortex. This system can be trained to reach short/long-term memory (STM/LTM) by the iteration of EPSC or IPSP. After a short-time adaptation, the sensitivity of eyes quickly changed to a suitable level similar to the surroundings. Chai *et al.* demonstrated an in-sensor computing to achieve powerful and efficient artificial visual systems[3]. Conventional image sensors can faithfully detect visual information, but generate a lot of redundant data. The large amount of data passed through the entire signal chain, resulting in a large delay (latency) and high power consumption. As a contrast, the in-sensor computing can avoid these inefficient movements and enable visual systems to achieve real-time processing and decision-making abilities. Thus, a powerful and reliable artificial vision system can be realized for various applications such as driverless vehicles, robot or industrial manufacturing.

Inspired by human vision system, an artificial neural network (ANN) (Fig. 1(h)) was designed with similar hierarchical structure. ANN can reset its weight values (learning) by comparing the outputs with existed examples or by analyzing without examples. The more iteration ANN operates, the smarter it can be in the application of visual intelligence. Mennel *et al.* constructed an ANN with 9 code-layer neurons and successfully achieved the training of the classifier and auto encoder (Fig. 1(i)). Neuromorphic vision system shows a great promise due to its low energy consumption and high-speed computation. The artificial intelligence using TMDCs-based devices may find wide applications in driverless car, smart surveillance, intelligent healthcare, etc. The semiconducting and mechanical properties of TMDCs also allow them to be used in auditory and tactile devices[11].

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