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Research and Application of Visual Object Recognition System Based on Deep Learning and Neural Morphological Computation

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ABSTRACT

The development of advanced optoelectronic vision sensors for high-level image recognition and data preprocessing is poised to accelerate the progress of machine vision and mobile electronic technology. Compared to traditional sensory computing methods, such as analog-to-digital signal conversion and digital logic computation tasks (i.e., Von Neumann computing), neural morphological vision computing can significantly improve energy efficiency and data processing speed by minimizing unnecessary raw data transmission between front-end photosensitive sensors and back-end processors. Neural morphological vision sensors are typically designed for tasks such as denoising, edge enhancement, spectral filtering, and visual information recognition. These methods can be categorized into approaches using near-sensor and sensor-internal computing processors based on whether preprocessing can be performed in situ. In near-sensor computing approaches, the image sensor for capturing visual information and the memory computing processor for preprocessing captured images are separate. A memory computing processor can simultaneously perform memory and computing tasks based on analog memory functions. Neural morphological vision sensors for in-sensor computing can be constructed using single-element image sensors, enabling both the reception of visual information and the execution of memory computing processes to be achieved in the same device. This represents an ideal scenario for future artificial intelligence machines and mobile electronic devices in visual computing systems.

KEYWORDS

Optoelectronic vision sensors; Advanced image recognition; Neural morphological computing; Mobile electronic technology.

1. INTRODUCTION

In the era of artificial intelligence, traditional computing systems based on von Neumann architectures are facing significant challenges, such as the inherent upper limit of computing speed and the dramatic increase in energy consumption, which can be attributed to the separation of processing and storage units. To overcome this dilemma, researchers have been trying to find a more efficient system. Among them, neuromorphic computing based on artificial synapses shows great advantages such as high-speed computing, ultra-low energy consumption of perception, learning and memory, and is expected to become an important method to solve the above problems. Compared with neuromorphic devices regulated by electrical signals, which have been widely studied, photoelectric synaptic devices contain many remarkable characteristics, such as low crosstalk, high anti-interference, low power consumption, etc., and are more suitable for ultra-high-speed computing. In addition, the development of artificial vision with flexibility, complexity and adaptability brought about by the research of light-stimulated synaptic devices will play an important role in human life. Recently, organic materials, metal oxides, graphene, MoS2, WSe2 and other two-dimensional materials have been used to make photoelectric synapses, showing remarkable performance. However, many of these materials require complex and expensive preparation methods, which is not conducive to the advancement of large-scale and low-cost flexible synaptic devices. Most of the reported work focuses on the realization of basic synaptic properties, and little is involved in further development of device functions. In addition, with the rapid development of wearable electronic devices, there is an increasing demand for flexible devices with ultra-low energy consumption, robust bending stability and powerful data processing capabilities. Therefore, it is imperative to find low-toxicity flexible synaptic devices and expand research and application to solve the above obstacles.

As a result, deep learning technology has flourished in the field of computer vision, bringing revolutionary breakthroughs for tasks such as image recognition, object detection, and scene understanding. Central to this development lies the rise of deep neural networks, whose powerful feature extraction capabilities allow computers to better understand and interpret image content. Through the training of large-scale data sets, deep learning systems can automatically learn complex image features and realize accurate recognition and understanding of various complex scenes. In addition, with the continuous advancement of computer hardware technology, such as the widespread application of Gpus and Tpus, and the development of distributed computing, the speed and efficiency of deep learning models in the training and reasoning process have been significantly improved. The development of these technologies provides a broader prospect for the application of deep learning and computer vision recognition systems, and lays a solid foundation for the realization of intelligent perception and cognitive systems.

2. RELATED WORK

2.1. Neuromorphic computation

The concept of neuromorphic computing originated in the late 1980s, and this approach has been particularly prominent in the advancement of deep learning applications and has great potential. Deep learning is an increasingly common form of artificial intelligence (AI) that utilizes brain-inspired neural networks to reveal patterns in large data sets. In traditional machine learning using conventional computer hardware, the location of memory and processing nodes is separate. Instead, neuromorphic computer hardware mimics neurons and puts the two functions in the same place. The architecture eliminates the need to transfer data back and forth between processing sites and storage sites, thus greatly reducing the computational time and power requirements for certain specific learning tasks, such as image recognition and classification.

Although the concept of neuromorphic computing originated in the late 1980s, its development has been hampered by the slow pace of algorithm development, the need for novel materials to build integrated memory/processing nodes, and challenges in scaling up. According to Thomas Cleland, a psychology professor at Cornell University in Ithaca, New York, early neuromorphic neural networks were not malleable. Once set up, they can only be trained to complete one specific task. To accomplish other tasks, it needs to be rebuilt and retrained. This limitation, Cleland says, has "very big limitations."

2.2. Neuromorphic computing and deep neural networks

In recent years, neuromorphic has been used to describe analog, digital, analog/digital hybrid mode VLSI and software systems capable of implementing nervous system model functions such as perception, motor control, multisensory integration, etc. Hardware implementations of neuromorphic computing can be achieved through oxide-based Memristor (memristor), spintronic memory, threshold switches, and transistors. Training of a software-based pulsed neural network system can be achieved through error backpropagation mechanisms, for example, using a Python-based framework such as snnTorch, or a typical biologically-inspired learning model such as BindsNet.

Therefore, combined with deep neural networks, neuromorphic computation and computer recognition systems can be effectively achieved with higher efficiency. Compared with traditional DNNS, the unit of a typical DNN emits an output value, so the frequency of energy consumption is several orders of magnitude higher. However, determining which types of DNNS can be implemented in an energy-efficient way with sparsely active neurons in neuromorphic hardware for use in modern AI solutions remains an open question.

This effect is known in neuroscience as peak-frequency adaptation. Experimental data from the Allen Institute suggest that a significant number of neurons in the neocortex (more than 30% of excitatory neurons in the human frontal lobe) exhibit spiking frequency adaptation. The study shows that AHP neurons not only save energy by reducing their firing activity, but also provide a true alternative to LSTM units for solving sequence processing tasks and support training via time backpropagation (BPTT).

Another major difference between biological neurons and the standard pulse-neuron model is that biological neurons keep their membrane potential within a relatively narrow range. In contrast, when the network is trained using regularization terms to induce low discharge rates, the model's membrane potential will typically appear extremely negative. This effectively removes many of them from current network computing.

Intelligent analysis of CT images through AI technology can provide doctors with more objective and accurate diagnosis basis, thereby improving the efficiency and accuracy of diagnosis and treatment. [14]At the same time, AI technology can also help doctors quickly locate the lesion site and reduce missed diagnosis and misdiagnosis. In the future, with the continuous development and improvement of AI technology, the application of AI+CT imaging technology will be more extensive, providing more help and support for medical diagnosis and treatment.

2.3. Computer recognition and neuromorphic computation

Neuromorphic computing is regarded as a promising non-von computing paradigm, the core idea of which is to imitate the information processing of biological nervous system. To advance neuromorphic computing, researchers have developed a variety of novel devices, including programmable resistance switching devices and neuromorphic transistors. These devices successfully simulate the behavior of neurons and synapses and have been widely used in hardware accelerators of artificial neural networks as well as in biological sensing functions. To adapt to the development needs of the post-Moore era. The fabrication of neuromorphic devices should be as compatible as possible with the current mainstream CMOS integrated circuit technology. This will help preserve the key properties of neuromorphic computing while facilitating the development of higher level and intelligent AI systems.

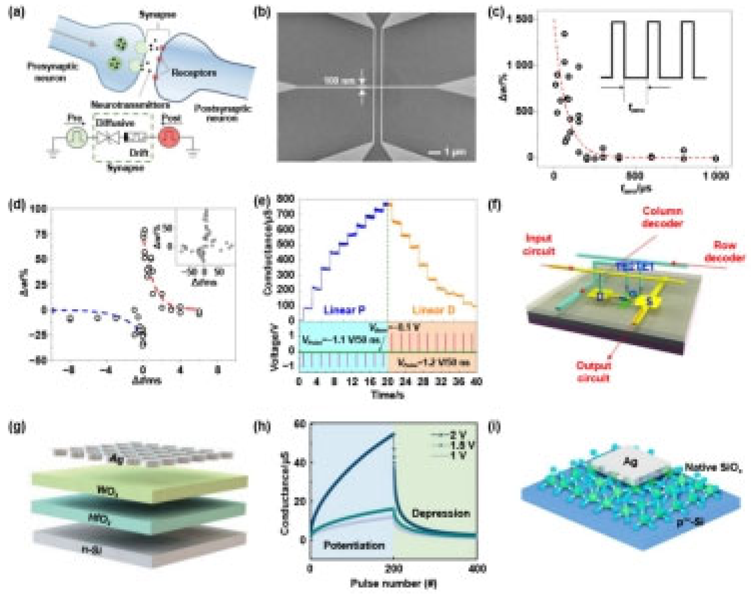

Figure 1: Plasticity simulation based on programmable resistive switching devices. (a) Schematic diagram of biological synapses and circuit models. (b) Scanning electron microscope photographs of nanoscale cross arrays. (c) Pulse frequency dependent plasticity learning rules. (d) Pulse time dependent plasticity learning rules. (e) bidirectional adjustable conductive characteristics. (f) Device architecture for simulating brain-like systems. (g) Schematic diagram of n-Si/HfO2/WO3/Ag structure. (h) bidirectional adjustable conductive characteristics. (i) Schematic diagram of a SiOx/p++-Si device with Ag/ atom thickness

These latest plasticity simulation techniques are based on programmable resistive devices and combine the biological characteristics and circuit models of biological synapses, demonstrating the latest developments in neuromorphic computing and computer recognition and perception systems. Using scanning electron microscope photographs of nanocross arrays and plasticity learning rules related to pulse frequency and time, these techniques achieve conductive behavior with bidirectional tunable characteristics. The device architecture includes the n-Si/HfO2/WO3/Ag structure and the SiOx/p++-Si device, which simulates the working principle of the brain-like system. These innovations provide a new direction for the development of intelligent sensing systems and promote the further development of artificial intelligence technology.

3. METHODOLOGY

The main methodological overview of this paper is that two-dimensional layered WSe2 nanosheets grown by salt-assisted chemical vapor deposition achieve the coexistence of analog and digital resistance in a vertically structured Pt/WSe2/Pt memristor. The memristor based on WSe2 exhibits excellent digital resistive behavior with high switching ratio, good stability and reliability, indicating potential applications of non-volatile memory.

On the other hand, simulated resistive behavior can be observed at low operating voltages. In addition, the memristor can be used as an artificial synapse to simulate basic synaptic functions, such as long-term enhancement and suppression and paired pulse promotion. More importantly, the learning-forgetting behavior of human brain can be successfully simulated, and the artificial neural network can be constructed for file type and image recognition with high precision.

3.1. Digital and analog resistance behavior

Resistive properties of two-dimensional WSe2 nanosheets, and synaptic function simulation and neuromorphic computation based on the memristor. It is found that the digital and analog resistive behavior depends on the operating voltage. Digital resistance with two resistance states can be achieved at high operating voltages. Simulated resistive behavior with a range of adjustable resistance states is achieved at relatively low operating voltages.

In addition, memristors can not only realize basic synaptic functions such as long-term enhancement, inhibition, and paired pulse promotion, but also successfully simulate human learn-forget behavior. At the same time, it can be used to construct a three-layer artificial neural network to realize image recognition. The coexistence of digital and analog rheotropic behavior in two-dimensional WSe2 nanosheets indicates potential applications in nonvolatile memory and neuromorphic computing.

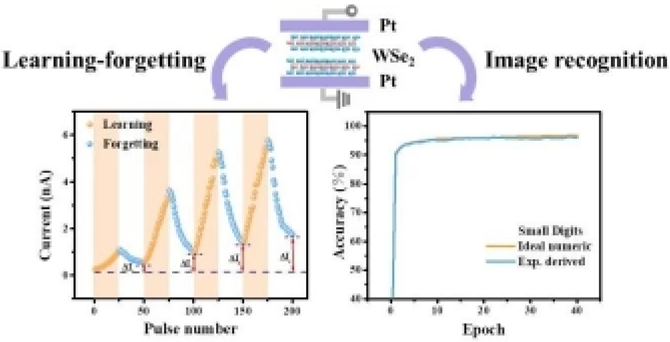

Figure 2: Three layer artificial neural network to realize image recognition

3.2. SEM, Raman, XPS characterization

WSe2 nanosheets were successfully prepared by means of SEM, Raman, XPS and other characterization methods. The thickness of the nanosheets obtained by AFM characterization is about 3.6nm and the number of layers is about 5.

Characterization of two-dimensional layered WSe2 on CVD growth: (a) Optical image of WSe2 growing on SiO2/Si substrate at 280 nm, illustrated with structural diagram of WSe2; (b) SEM images of WSe2; (c) AFM image of WSe2. The illustration shows the height contour corresponding to the white line in the AFM image; (d) Raman spectra of WSe2; (e) W 4f XPS spectrum; (f) Se 3d XPS spectrum.

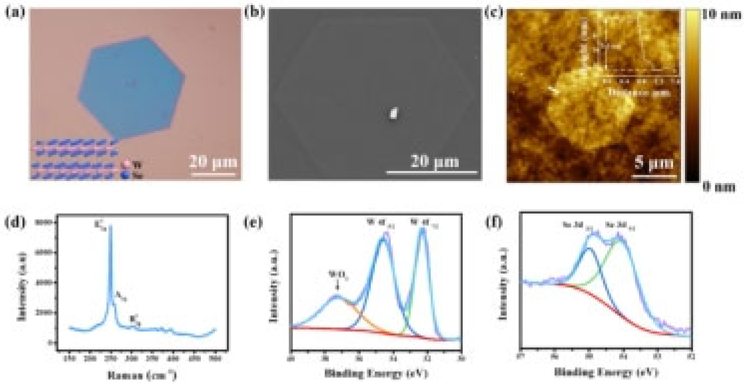

Figure 3: Characterization of two-dimensional layered WSe2 on CVD growth: (a) An optical image of WSe2 growing on a 280 nm SiO2/Si substrate, illustrated with a structural diagram of WSe2; (b) SEM images of WSe2; (c) AFM image of WSe2. The illustration shows the height contour corresponding to the white line in the AFM image; (d) Raman spectra of WSe2; (e) W 4f XPS spectrum; (f) Se 3d XPS spectrum.

It can be inferred from the above figure that neuromorphic computing may play a role in analyzing and processing image features. The successful preparation of WSe2 nanosheets requires the analysis of a variety of characterization methods, including scanning electron microscopy (SEM), Raman spectroscopy, and X-ray photoelectron spectroscopy (XPS). Atomic force microscopy (AFM) showed that the thickness of WSe2 nanosheets is about 3.6 nm and the number of layers is about 5 layers. Through the analysis of these images and spectral data, neuromorphic computation may identify and extract the characteristics of WSe2 nanosheets, such as morphology, thickness, crystal structure, etc., thus providing important information for subsequent research on material properties and applications. In addition, neuromorphic calculations may be used to create mathematical models of WSe2 nanosheets to further understand their formation mechanisms and physical properties during CVD growth.

3.3. Pt/WSe2/Pt memristor

Pt/WSe2/Pt memristors can also mimic learning-forgetting behavior in the human brain. Over the four learning cycles, cognitive levels gradually improve, and, in the process of "relearning", less learning is required to reach the same cognitive level as the first learning.

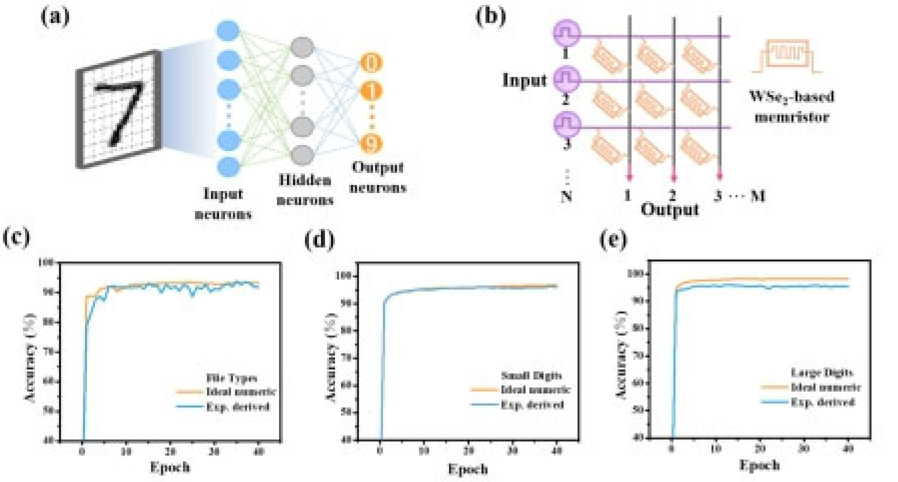

Figure 4: Neuromorphic calculation of Pt/WSe2/Pt memristor: (a) Schematic diagram of a three-layer artificial neural network; (b) A memristor-based cross-array circuit for matrix operations; (c-e) Changes in recognition accuracy of file type, small hand and large hand numerals over training time.

Based on the CrossSim platform, a three-layer artificial neural network composed of input layer, hidden layer and output layer is established to classify data sets of Sandia files. 8 × 8 pixel handwritten digital images from the "Handwritten digital Optical Recognition" dataset and 28 × 28 pixel handwritten digital images from the MNIST dataset were recognized. After 40 training cycles, the recognition accuracy of file type can reach 90.3%, the recognition accuracy of large image can be maintained at 95.4%, and the recognition accuracy of small image is as high as 95.9%, which is close to the limit of neuromorphic algorithm.

Therefore, in this paper, the author realized the coexistence of digital and analog resistance in a memristor with WSe2 nanosheets grown by salt-assisted chemical vapor deposition, and systematically studied the electrical synaptic behavior based on WSe2 memristors. At high voltage, the memristor exhibits a typical nonvolatile bipolar digital resistive behavior, with a high switching ratio of 6.3 × 104, good durability and retention characteristics, and has broad application prospects in nonvolatile memory.

On the other hand, simulated resistive behavior with a range of adjustable resistance states can be achieved at relatively low operating voltages. Memristors based on WSe2 can act as artificial synapses to perform basic synaptic functions, including long-term enhancement and suppression and paired pulse promotion.

In addition, learning-forgetting behavior can be simulated with the stimulation of a pulse voltage. What's more, artificial synapses can build artificial neural networks to achieve high-precision image recognition. Among them, the recognition accuracy of small image can reach 95.9%, which is close to the limit of neuromorphic algorithm. This study shows that the coexistence of digital and analog rheotropic behavior in two-dimensional WSe2 nanosheets can not only be used for non-volatile storage, but also demonstrates potential in neuromorphic computing.

4. CONCLUSION

The integration of neuromorphic computing and deep learning has broad application prospects in visual object recognition systems. Through the combination of neuromorphic computing and deep learning described in this paper, efficient energy utilization and data processing speed can be achieved, providing a new way for the development of visual object recognition systems. Deep learning technology has made a major breakthrough in the field of image recognition, and the introduction of neuromorphic computing has further improved the efficiency and accuracy of the system. This integration can not only accelerate the progress of machine vision technology, but also promote the development of mobile electronics technology, and lay a solid foundation for the realization of intelligent perception and cognitive systems.

The joint study of neuromorphic computing and computer recognition systems based on two-dimensional WSe2 nanosheets provides a new direction for the development of intelligent sensing systems. By analyzing the physical properties of WSe2 nanosheets and its application in neuromorphic computing, a novel neuromorphic computing device was presented in this paper, and its application in computer recognition systems was discussed. This research provides new ideas and possibilities for the development of intelligent sensing system, and provides a new direction for the continuous progress and application of artificial intelligence technology.

In summary, the integration of neuromorphic computing and deep learning will bring new opportunities and challenges for the development of visual object recognition systems, and the research on neuromorphic computing devices based on two-dimensional WSe2 nanosheets provides new technical support and theoretical basis for the realization of intelligent perception systems.

ACKNOWLEDGEMENT

In this study, we discuss the application of deep learning and neuromorphic computing in visual object recognition systems. We delve into the principles and practices of these technologies and explore their potential real-world applications. We drew on the work of experts in many fields, including a researcher specializing in deep learning and artificial intelligence. This researcher has a pair of enthusiastic eyes and a focused expression, and his work provides important inspiration and reference for our research.

In addition, we also learned from the research results of Chen, Wangmei and others. In their article, they use machine learning algorithms to optimize the personalized education recommendation system, which provides important technical support for personalized learning. Their research results provide valuable experience and guidance for us to understand and apply machine learning algorithms.

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