In-Sensor Visual Adaptation with Two-Dimensional MoS_2 Phototransistors

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ABSTRACT

Machine vision systems that capture images for visual inspection and identification tasks have to be able to perceive a scene under a range of illumination conditions. To achieve this, current systems use circuitry and algorithms that compromise efficiency and increase complexity. Here we report bioinspired vision sensors that are based on molybdenum disulfide phototransistors and exhibit time-varying activation and inhibition characteristics. Charge trap states are intentionally introduced into the surface of molybdenum disulfide, enabling the dynamic modulation of the photosensitivity of the devices under different lighting conditions. The light-intensity-dependent characteristics of the sensors match Weber's law in which the perceived change in stimuli is proportional to the light stimuli. The approach offers visual adaptation with highly localized and dynamic modulation of photosensitivity under different lighting conditions at the pixel level, creating an effective perception range of up to 199 dB. The phototransistor arrays exhibit image contrast enhancement for both scotopic and photopic adaptation.

1 Introduction

The human visual system enables the recognition of various objects and visual information sensing in a complicated environment, which inspires the development of biomimicry visual systems through electronic devices for future artificial vision [1-5]. An artificial visual system usually consists of photoreceptors to perceive the visual inputs as digital images, a memory unit to store visual information, and a processing unit to conduct complex image processing tasks, such as pattern recognition and object detection [1-3]. For the current artificial visual system, state-of-the-art image sensors can continuously detect the images in real-time, but generate a large amount of redundant data compared with the human visual system, which occupies a large amount of storage space and causes high power consumption. In contrast, the sensory neurons in the retina in the human visual system can not only detect light stimuli, but also perform the first stage of image processing before more complex visual signal processing in the visual cortex of the human brain [9-10]. Additionally, the processing and memory units in the existing neuromorphic visual systems can not directly respond to optical stimuli, and require image sensor arrays to convert optical signals to electrical ones and pass to neuromorphic chips for further signal processing. It is highly demanded to develop multifunctional electronic devices that can integrate sensing, memory, and processing functions for a more efficient artificial visual system.

The development of machine vision (*e.g.*, intelligent vehicles, mobile medical, real-time video analysis, and cooperative autonomous driving) demands hardware with ultrahigh-resolution, high image capturing speed, more stabilization, and wide-range detection of different lighting conditions [2]. The accurate representation of wide-range light illumination is critical for the correct perception of the environment, because the natural light spans the light intensity with a very large range of 280 dB. It requires optoelectronic devices that can accurately capture and perceive more shadow and highlighted details. The state-of-the-art image sensors with Si CMOS technologies usually have a dynamic range of 70 dB, much narrower than the natural scene. To adapt the vision under a large illumination intensity range, researchers control the optical aperture, adopt a liquid lens, adjust the exposure time, and apply denoising algorithms in post-processing, which usually requires complex hardware and software resources. It is quite necessary to develop optoelectronic devices with visual adaptation functions and a wide perception range at sensory terminals, which can enrich machine vision functions, reduce hardware complexity, and realize high image recognition efficiency [5].

In this work, we designed an optoelectronic memory device with a simple two-terminal and three-terminal structure, which exhibits light sensing, optical triggered non-volatile and volatile resistance switching, and light tuneable synaptic behaviors. Through optoelectronic memory arrays, we experimentally demonstrated image sensing, image memorization, pre-processing, and light adaptation functions. Further simulations of neuromorphic visual systems prove that image pre-processing (background noise reduction) at the front-end can effectively improve the image quality, and increase the processing efficiency and the accuracy of subsequent image recognition.

2 Bioinspired in-sensor vision adaptation

The three-terminal MoS_2 phototransistor can well simulate the structure and function of the retinal plexus. The photosensitivity $S_{ph} = I_{ph}/I_{dark}$, (where I_{ph} is photocurrent, I_{dark} is drain current (I_D) under dark condition) and threshold I_D (=2I_{dark}) can be well controlled by the V_G according to the illumination power density. In addition, the I_D increases (decreases) gradually over time under a continuous illumination condition when applying a negative V_G (positive V_G) due to the charge de-trapping (trapping) mechanism. So that we can realize the visual adaptation function (both scotopic and photopic adaptation) by the three-terminal optoelectronic memories based on the time-varying excitation or inhibition characteristics depending on V_G and presents a high perception range up to 199 dB.

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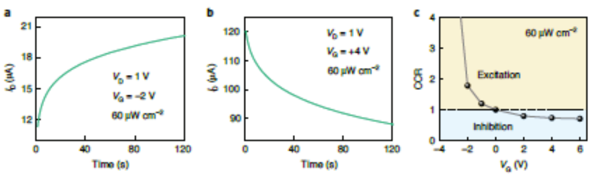

Fig. 1 Time-dependent current (I_D) of the device under continuous illumination of 60 μW cm^{-2} at V_G values of −2 V (a) and +4 V (b). (c) Extracted CCR at different V_G values [5].