

Tetrachromatic-inspired neuromorphic optoelectronic sensor based on $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterostructures for dual-band dynamic motion perception

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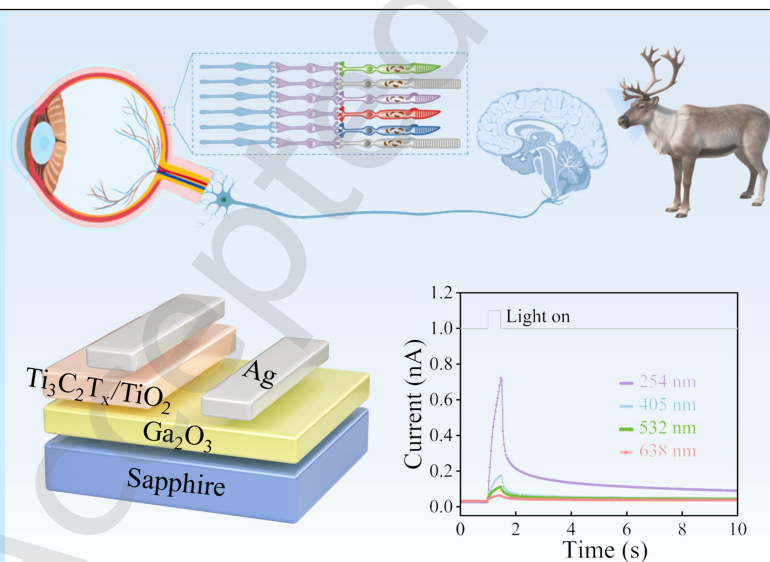
Tetrachromatic-Inspired Neuromorphic Optoelectronic Sensor based on $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ Heterostructures for Dual-Band Dynamic Motion Perception

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This study presents a tetrachromatic optoelectronic synaptic sensor based on a $\text{Ga}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ heterostructure, with responses at 254, 405, 532 and 638 nm. Drawing inspiration from reindeer tetrachromatic vision, we achieve UV-visible dual-band fusion for real-time identification of moving target direction and speed, offering a viable route toward high-precision dynamic perception in complex scenarios.

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ABSTRACT: Traditional image sensors face inherent trade-offs among accuracy, power consumption, and hardware complexity in dynamic recognition tasks. Drawing inspiration from the tetrachromatic vision of reindeer, we report a $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensor. The defect-rich TiO_2 interlayer, formed via native oxidation of 2D $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, constructs a Type-II heterojunction with Ga_2O_3 , dramatically boosting photogenerated carrier separation. The device exhibits multi-level photoresponses across four wavelengths (254–638 nm) and faithfully emulates key synaptic behaviors, including excitatory postsynaptic current (EPSC), paired-pulse facilitation (PPF) and spike-rate-dependent plasticity (SRDP). Based on a 20×20 array, we develop a dual-band (UV-visible) hybrid motion-perception system. Capitalizing on the pronounced conductance plasticity, this system effectively encodes spatial and temporal optical information. When coupled with a convolutional neural network, it achieves a remarkable 95.7% accuracy in recognizing complex trajectories, significantly outperforming conventional architectures. This work provides a versatile materials platform for broadband neuromorphic photodetection and paves the way for high-precision machine vision in complex environments.

KEYWORDS: tetrachromatic Vision, $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterostructures, neuromorphic optoelectronic sensor, oxygen vacancies/defect engineering, dynamic motion perception

1. Introduction

The intelligent recognition and comprehension of dynamic actions are pivotal to the advancement of the Internet of Things (IoT). [1–4] Action recognition fundamentally entails the processing of spatiotemporal data, which couples spatial configurations with temporal dynamics. Consequently, the effective encoding of this interconnected spatiotemporal information is a critical imperative. Conventional image sensors, however, are inherently limited in integrating temporal and spatial data simultaneously, which inevitably leads to elevated energy consumption, response latencies, and prohibitive hardware costs. [5–8] In contrast, biological visual systems excel at capturing salient features within complex environments, enabling efficient dynamic perception with exceptional accuracy. [9–12] Crucially, in the natural world, dynamic scenes are rarely confined to purely structural and motion vectors; instead, robust perception demands the orchestration of spatiotemporal trajectories alongside the rich spectral dimension. Benefiting from the sophisticated architecture of the retina, biological vision can seamlessly extract these multidimensional visual cues, concurrently resolving high-fidelity spatiotemporal details and complex

chromatic information. [13–15] While human vision is typically trichromatic relying on three types of photoreceptor cells sensitive to red, green, and blue (RGB) light certain species, [16–18] such as reindeer, hummingbirds, and lizards, possess tetrachromatic visual systems. This evolutionary adaptation allows them to perceive the ultraviolet (UV) spectrum alongside standard RGB bands. [19–21] By capturing richer spectral data than their trichromatic counterparts, tetrachromatic vision affords these animals profound evolutionary advantages in predator avoidance and foraging behaviors. [22] Inspired by this biological paradigm, the development of artificial tetrachromatic vision systems has emerged as a burgeoning frontier. To date, most research on dynamic recognition remains confined to low-level visual processing, such as noise suppression and short/long-term memory emulation. [23–25] In contrast, tetrachromatic systems hold immense potential for high-precision dynamic recognition in intricate scenarios. By leveraging UV-band sensitivity, these systems are uniquely suited for target recognition in low-light environments, heat source detection, and high-speed object tracking. Therefore, advancing neuromorphic optoelectronic sensors capable of multi-band image fusion is of paramount importance.

Owing to its ultra-wide bandgap, Ga_2O_3 has emerged as a premier candidate for solar-blind optoelectronics, characterized by an exceptionally high absorption coefficient in the deep-ultraviolet (DUV) regime, [26,27] viable pathways for cost-effective, large-scale production, [28] and robust stability under extreme operating environments. Consequently, Ga_2O_3 has been extensively deployed across diverse optoelectronic platforms, including light-emitting diodes (LEDs), [29] photodetectors, [30] and optoelectronic memristors. [31] Nevertheless, inherently constrained by its intrinsically wide bandgap, the spectral response of Ga_2O_3 -based devices remains predominantly restricted to the ultraviolet region, rendering the expansion of its spectral sensitivity a critical yet unfulfilled objective. Two-dimensional (2D) MXenes, a novel class of transition metal carbides, nitrides, or carbonitrides featuring a graphene-like morphology, have attracted widespread attention in the field of synaptic memristors. This interest is driven by their intrinsically tunable conductivity, ultra-fast charge response, compact stacking characteristics, and excellent mechanical durability. [32-34] Furthermore, MXenes exhibit robust hydrophilicity owing to their abundant surface functional groups, facilitating their seamless integration or growth on metal oxides. [35-38] Recently, neuromorphic optoelectronic sensors leveraging defect engineering within MXene matrices have been actively explored. [39-43] For instance, Lee et al. demonstrated a flexible MXene-based synaptic sensor that exhibits stable optical synaptic plasticity across a broad spectrum from visible to near-infrared (NIR) light by exploiting process-introduced intrinsic defects within the MXene matrix, maintaining performance integrity under mechanical deformation. [39] Separately, Li et al. proposed an electrically and optically co-modulated MXene synaptic memristor capable of emulating visual pain perception and achieving pattern-based infrared imaging under NIR stimulation. [34] Therefore, combining wide-bandgap Ga_2O_3 with oxidized MXenes to introduce defect states provides a synergistic approach for multi-band photoresponse, paving the way for advanced biomimetic tetrachromatic sensors.

In this work, we propose to utilize TiO_2 formed by the oxidation of MXene to construct a Type-II heterojunction with Ga_2O_3 , enabling carrier separation. Furthermore, by exploiting the defects introduced via oxidation, we successfully fabricate a tetrachromatic neuromorphic optoelectronic sensor. The device achieves response to optical stimulation at four wavelengths: 254 nm, 405 nm, 532 nm and 638 nm. Inspired by reindeer vision, we successfully realize dual-band (UV and visible) fusion-based dynamic motion perception and effectively encode spatiotemporal information using the conductance plasticity of the device, thereby enabling the perception of both direction and speed of moving targets. Combined with an artificial neural network, the recognition accuracy for different trajectory actions exceeds 95%. This study provides a feasible technical route for high-precision dynamic recognition in complex environments.

2. Results and discussion

Figure 1a schematically illustrates the workflow of reindeer visual perception, including the structure and function of photoreceptor cells (rod and cone cells) in the retina, the optic nerve, and synapses in the visual cortex. [44] Inspired by this biological neuromorphic paradigm to achieve tetrachromatic photoresponse, we designed a $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensor

that mimics retinal photoreceptors by converting optical signals into electrical signals; we successfully fabricated a 20×20 device array and, in conjunction with a convolutional neural network (CNN), emulated the classification processing of the visual cortex, as shown in the schematic and optical image in Figure 1b. The cross-sectional scanning electron microscopy (SEM) image and the energy dispersive spectroscopy (EDS) images of C, Ti, Ga, and O are presented in Figure 1c, disclosing a uniform total film thickness of approximately 420 nm. To elucidate the chemical composition of the oxidized MXene, X-ray photoelectron spectroscopy (XPS) was executed. Figure 1d displays the high-resolution Ti 2p XPS spectrum, wherein the prominent enhancement of the Ti-O peak after oxidation indicates a substantial proliferation of TiO_2 formed within the MXene. [45] Concurrently, the O 1s spectrum corroborates that the as-formed TiO_2 harbors abundant oxygen vacancies (Figure 1e). To monitor the lattice evolution during the oxidation of $\text{Ti}_3\text{C}_2\text{T}_x$, Raman spectroscopy was performed. As shown in Figure 1f, the characteristic Raman peak at 152 cm^{-1} is prominently intensified after 48 hours of oxidation, which is directly benchmarked against the formation of TiO_2 . [46] Tracking the Raman spectra under varied oxidation durations (Figure S1) further authenticates this structural transformation, revealing that the 152 cm^{-1} peak intensity scales as the oxidation process prolongs. Furthermore, the ultraviolet-visible (UV-vis) absorption spectra of both pristine Ga_2O_3 and the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ composite films are evaluated in Figure 1g. Pristine Ga_2O_3 exhibits a sharp absorption edge restricted to the deep-UV region, corresponding to its wide bandgap of 4.7 eV. [47] In contrast, the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterostructure presents a broad, continuous absorption profile spanning across both UV and visible spectra. This provides favorable conditions for the subsequent realization of tetrachromatic synapses. Figure 2a shows a schematic diagram of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ photosensors. The photoresponse characteristics of the photosensors were evaluated for different $\text{Ti}_3\text{C}_2\text{T}_x$ oxidation times (0, 24, 48, and 72 hours), as shown in Figure S2. Under a bias of 10 V, the responsivity exhibited a trend of initially increasing and then decreasing with increasing oxidation time. Notably, the device based on a $\text{Ti}_3\text{C}_2\text{T}_x$ film oxidized for 48 hours demonstrated the best photodetection performance, with a responsivity exceeding 128 mA/W and a detectivity as high as 3×10^{13} Jones. This result confirms that precise control of the oxidation time is an effective strategy for tuning the photodetection performance of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ structure. However, excessively long oxidation times lead to a decrease in both responsivity and detectivity. This indicates that over-oxidation severely compromises the inherent high conductivity of $\text{Ti}_3\text{C}_2\text{T}_x$, and the formation of excess TiO_2 significantly impedes carrier transport within the heterojunction device.

To systematically evaluate the performance of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ solar-blind UV photosensor, the current-voltage (I-V) characteristics of the pristine Ga_2O_3 device and the optimized $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device (oxidized for 48 hours) were measured under dark conditions and under 254 nm illumination, respectively, as shown in Figure 2b. Clearly, the introduction of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ layer enhances the

photocurrent while suppressing the dark current. Furthermore, the current-time (*I-t*) curves show that the photodark current ratio significantly increased from 600 to 2500 (Figure S3).

Moreover, the wavelength-dependent detectivities of the pristine Ga_2O_3 Schottky device and the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterojunction device was investigated. As shown in Figure 2c, Notably, the detectivity of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device reached 1.19×10^{13} Jones at 254 nm, representing a significant improvement over the pristine Ga_2O_3 device. To further elucidate the intensity-dependent response characteristics of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device, Figure 2d shows that the photocurrent increases with increasing incident light intensity and exhibits excellent repeatability. Under an irradiance of $3.66 \mu\text{W}/\text{cm}^2$, the photocurrent reached 3.9 nA, and at a higher irradiance of $16.87 \mu\text{W}/\text{cm}^2$, the

photocurrent further increased to 22.7 nA. Conversely, as shown in Figure 2e, the responsivity exhibited a decreasing trend with increasing incident light intensity. Notably, at a light power density of $3.66 \mu\text{W}/\text{cm}^2$, the responsivity of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device ($128.65 \text{ mA}/\text{W}$) is 38.9 times that of the pristine Ga_2O_3 Schottky device ($3.31 \text{ mA}/\text{W}$). This strongly validates that the introduction of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ composite structure significantly enhances the optoelectronic performance of the Ga_2O_3 solar-blind UV photosensor. Furthermore, as shown in Figure 2f, the decay time of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ photosensor (defined as the time required for the current to drop from 90% of its peak to 10%) is significantly longer than that of the pristine Ga_2O_3 device. This suggests that the introduction of the heterojunction interface may have generated localized trap states, thereby prolonging the carrier extraction process.

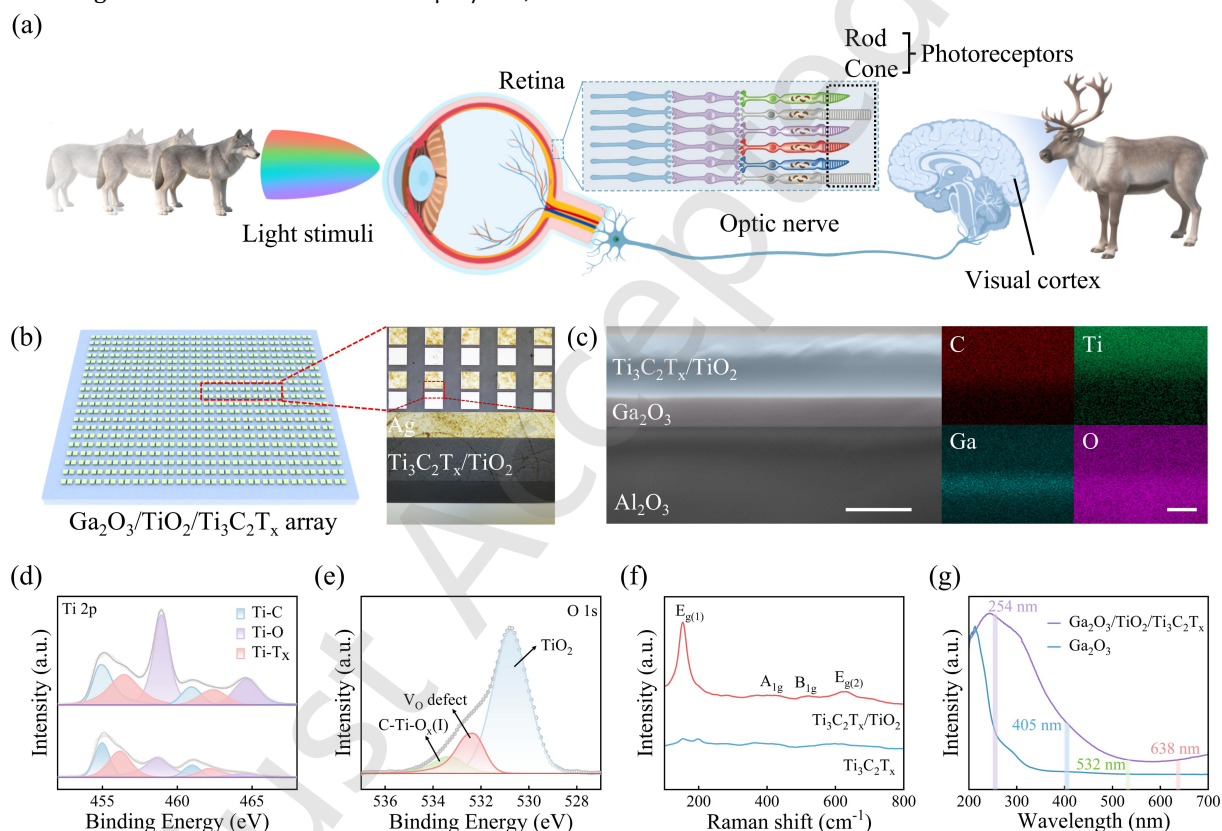


Figure 1. $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensor for neuromorphic vision. (a) Schematic diagram of the reindeer visual perception system. (b, c) Schematic diagram, optical microscopy image, cross-sectional view, and EDS mapping of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensors. Scale bar, 200 nm. (d) Ti 2p XPS spectra of $\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ and $\text{Ti}_3\text{C}_2\text{T}_x$ films. (e) O 1s XPS spectrum of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ film. (f) Raman spectra of $\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ and $\text{Ti}_3\text{C}_2\text{T}_x$ films. (g) Absorption spectra of $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ and Ga_2O_3 films.

To elucidate the operating mechanism of the high-performance $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterojunction solar-blind UV sensor, the band diagrams of Ga_2O_3 , TiO_2 , and $\text{Ti}_3\text{C}_2\text{T}_x$ prior to contact are shown in Figure 2g. According to previous reports, the conduction band and valence band edges of Ga_2O_3 (TiO_2) are located at -4.0 eV (-2.48 eV) and -8.7 eV (-5.55 eV), respectively. [47,48]

Through UPS measurements, the work function of $\text{Ti}_3\text{C}_2\text{T}_x$ was determined to be 5.36 eV, as shown in Figure S4. Furthermore, since the Fermi level of TiO_2 is higher than that of Ga_2O_3 , this difference in electronic structure leads to the formation of a built-in electric field at the interface pointing from TiO_2 toward Ga_2O_3 , thereby forming a typical Type-II heterojunction, as shown in Figure 2h. When the

heterojunction photosensor is exposed to solar-blind UV illumination, photogenerated holes migrate from Ga_2O_3 toward TiO_2 driven by the built-in electric field, subsequently entering the $\text{Ti}_3\text{C}_2\text{T}_x$ layer, and are ultimately collected by the external circuit. Conversely, photogenerated electrons move in the opposite direction under the influence of the built-in electric field. The presence of the TiO_2 interface layer effectively promotes the spatial separation and migration of photogenerated carriers, thereby reducing the probability of electron-hole recombination. At the same time, the excellent conductivity of $\text{Ti}_3\text{C}_2\text{T}_x$ accelerates charge transfer, ultimately enhancing device performance. This dual-interface synergy significantly improves the separation

efficiency and transport rate of photogenerated carriers. Furthermore, the rough surface of $\text{Ti}_3\text{C}_2\text{T}_x$ resulting from moderate oxidation increases the effective interface area of the heterojunction, providing abundant active sites for carrier separation and further improving extraction efficiency. Thanks to this band engineering, the heterojunction device exhibits significantly enhanced photoresponse characteristics.

Profiting from the Type-II heterojunction formed between Ga_2O_3 and the TiO_2 derived from MXene oxidation, efficient carrier separation is achieved, thereby laying a solid foundation for the realization of the neuromorphic optoelectronic sensor. Furthermore, a β value of 0.59 was extracted from the intensity-photocurrent (I-P) characteristic curves (Figure S5), signaling the presence of a high density of defects within the thin film. These defects

partially originate from the structural or chemical imperfections (such as functional groups, grain boundaries, and vacancies) introduced during the MXene preparation. [39] Another significant portion stems from the oxygen-related defects generated during the oxidation process; this is further substantiated by the O 1s XPS spectrum of TiO_2 in Figure 1e, which clearly confirms the defect-rich nature of the as-grown TiO_2 . Furthermore, we measured the UV-Vis absorption spectra of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ films with different oxidation times and found that as the oxidation time increased, the absorption spectrum broadened to 638 nm (as shown in Figure S6), which is also attributed to the generation of defect-state TiO_2 during the oxidation process. Ultimately, these abundant defects provide highly favorable conditions for achieving the tetrachromatic neuromorphic optoelectronic sensors.

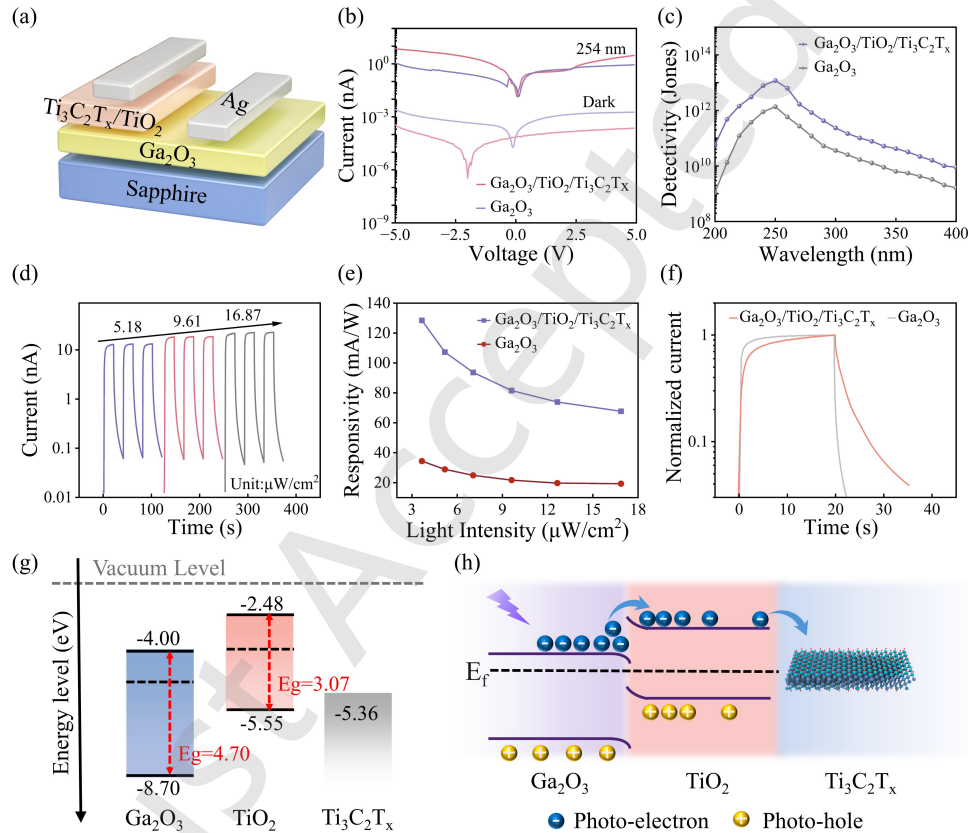


Figure 2. Photodetection performance and operating mechanism of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterojunction photosensor. (a) Schematic diagram of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ photosensor. (b) Current-voltage (I-V) characteristics of the pristine Ga_2O_3 device and the optimized (oxidized for 48 hours) $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device under dark conditions and at 254 nm illumination. (c) Wavelength-dependent detection efficiency curves for the Ga_2O_3 Schottky sensor and the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterojunction sensor. (d) Current-time response curves of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device under different incident light intensities. (e) Trend plots of the responsivity of the Ga_2O_3 Schottky sensor and the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device as a function of incident light intensity. (f) Normalized current versus time curves, indicating that the photoresponse and decay time of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ sensor are longer than those of the pristine Ga_2O_3 device. Band structure diagrams of Ga_2O_3 , TiO_2 , and $\text{Ti}_3\text{C}_2\text{T}_x$ before (g) and after (h) contact, illustrating the photodetection mechanism of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device.

In a biological neural network (Figure 3a), external stimuli induce action potentials at the presynaptic terminal to trigger the release of neurotransmitters across the synaptic cleft toward the postsynaptic membrane, thereby yielding a postsynaptic current. When the stimulus is removed, neurotransmitters at the postsynaptic membrane gradually deplete, and the postsynaptic current slowly returns to baseline levels. [49-52] For the constructed neuromorphic optoelectronic sensor, light stimulation and the conductive pathway emulate the dual roles of the presynaptic input and the postsynaptic membrane in a

biological synapse. Based on this configuration, the device successfully simulates the typical EPSC behavior of biological synapses. Figure 3b shows the multi-wavelength enhancement behavior of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device under laser irradiation at 254 nm, 405 nm, 532 nm, and 638 nm. The results indicate that as the wavelength increases, the induced EPSC gradually decreases, which is consistent with the absorption curve of the oxidized $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ film. Figure 3c displays the EPSC responses after applying multiple pulses at different wavelengths. Notably, with an increasing number of pulses,

the photocurrent rises progressively, accompanied by a more pronounced divergence in the induced EPSC amplitudes among the different wavelengths. Additionally, we characterized the photoresponse currents of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensors prepared with different $\text{Ti}_3\text{C}_2\text{T}_x$ oxidation durations under 254, 405, 532 and 638 nm light irradiation (Figure S7). The results indicate that with prolonged oxidation time, the device's spectral response range broadens to 638 nm, which further confirms that the generation of defect-state TiO_2 broadens the response spectrum.

The temporal correlation can be implemented by applying two consecutive light pulses to $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device. Figure 3d illustrates the PPF behavior of the device induced by a pair of light pulses (pulse width, interval time = 1 s). The PSC peak A_2 induced by the second light pulse is significantly enhanced compared to the PSC peak A_1 induced by the first light pulse. The PPF index is defined as $\text{PPF index} = A_2/A_1$, and its dependence on the interval time (Δt) is shown in Figure 3e, which can be fitted by the following double exponential decay function: [53-56]

$$\text{PPF}(\Delta t) = C_1 \exp\left(-\frac{\Delta t}{\tau_1}\right) + C_2 \exp\left(-\frac{\Delta t}{\tau_2}\right) \quad (1)$$

where C_1 and C_2 represent the initial facilitation magnitudes, and τ_1 and τ_2 represent the characteristic relaxation times.

The dependence of the EPSC on pulse frequency is shown in Figure 3f. It can be observed that under light pulses of different wavelengths, the device exhibits stronger excitation at higher frequencies, which is similar to the SRDP function observed in biological synapses. Moreover, the multi-wavelength capability of the device enables the successful emulation of synergistic learning, forgetting, and

relearning processes under diverse optical pulses ranging from the deep ultraviolet to the visible spectrum (Figure S8). To demonstrate the technical advantages of our work in realizing tetrachromatic synaptic behaviors, we have also conducted a comparative analysis with other reported neuromorphic optoelectronic sensor material systems (see Table S1 in the Supporting Information). To analyze the effect of light stimulation modulation on synaptic performance, in-situ Kelvin probe force microscopy (KPFM) measurements were performed on the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ film, as shown in Figure 3g. First, the composite film exhibits a contact potential difference (CPD) of approximately 75 mV over a $10 \mu\text{m} \times 10 \mu\text{m}$ area. Upon visible light illumination, the surface potential of the composite film gradually increases, and the extent of the increase becomes more pronounced as the wavelength decreases. This is attributed to the capture and accumulation of photoexcited holes (generated by the oxidized MXene) at defect states. Under deep ultraviolet light illumination, owing to the intrinsic strong absorption of Ga_2O_3 in the deep ultraviolet region, a massive number of photogenerated electron-hole pairs are yielded, whereupon the holes are captured and accumulated by defects in the MXene, leading to a significant increase in surface potential. This behavior corresponds to the observations in Figures 3b and 3c. Meanwhile, we also performed KPFM measurements on a pure Ga_2O_3 film and found that the surface potential changed only under deep ultraviolet illumination, with no change under visible light irradiation. This result verifies that the oxidized MXene provides favorable conditions for realizing tetrachromatic synapses (Figure S9).

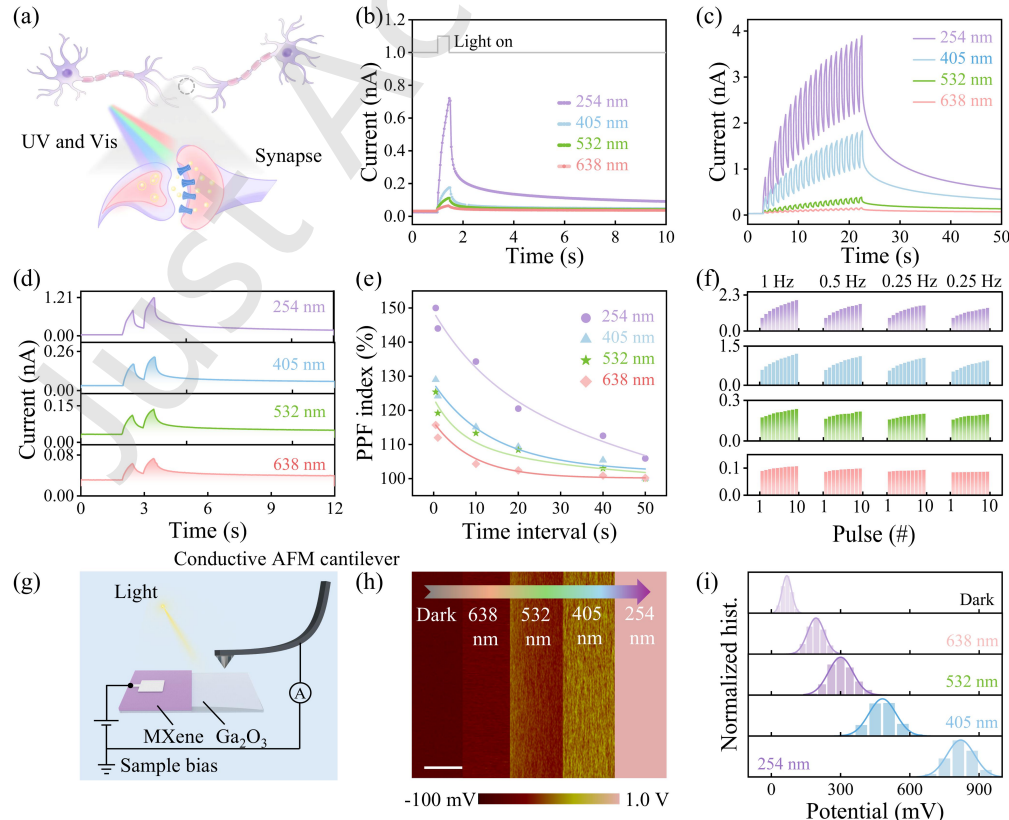


Figure 3. Multiwavelength modulation of synaptic plasticity in $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ tetrachromatic neuromorphic optoelectronic sensors. (a) Schematic diagram of synaptic weights modulated by four-color light illumination. (b) Photocurrent of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device under four-color light illumination. (c) Photocurrent under excitation of 20 four-color light pulses. (d) Synaptic PPF behavior of the device under four-color light

irradiation. (e) Dependence of the PPF index on Δt . (f) Frequency-dependent EPSC recorded under four-color light pulses. (g) Schematic diagram of in situ KPFM measurement of the surface potential of a $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ film. (h) Surface potential distribution of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ composite film under four-color light irradiation. Scale bar, 3 μm . (i) Surface potential difference histogram of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ composite film under four-color light irradiation.

Leveraging the multilevel response characteristics of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensor across different wavelength bands enables efficient temporal information encoding at the sensory terminal, thereby facilitating dynamic motion perception. As illustrated in Figure 4a, the presence of light is regarded as a pulse “1”, and the absence of light as “0”. Under four different temporal sequences of light pulse encoding, the conductance response of the device exhibits 16 distinct conductance states. Inspired by the visual system of reindeer, we propose a dual-band hybrid dynamic motion perception system. Notably, although the individual device responds to four wavelengths (254, 405, 532 and 638 nm), this work does not employ it for four-channel parallel color discrimination. Instead, capitalizing on this multi-wavelength response characteristic, we constructed a dual-channel system composed of two independent 20×20 neuromorphic optoelectronic sensor arrays, intended for efficient and accurate motion recognition. Taking a rocket model as the target object, the two photosensitive units simultaneously detect incident light pulses in the visible and DUV spectral ranges, respectively, and convert them into graded photocurrent signals that are transmitted to a computer. By applying neural network algorithms, the computer processes and encodes the dual-band photosensitive data, presenting the

contour of the target rocket model and its exhaust plume in the fused dual-band visual image, thereby enabling real time target recognition and motion perception.

Figure 4b illustrates the process of fusing visible light and temporally sequential DUV images into a dual band perception image using synchronous encoding technology. We performed optoelectronic measurements at a sampling frequency of 1 Hz. Under visible and DUV light pulse excitation, four consecutive time sequential images were obtained in the respective spectral ranges. Subsequently, computer software was used to perform spatiotemporal modulation fusion on the dual-band images acquired at the same time instant, enabling high precision image recognition and motion perception of the target object. Figures 4c-4f show the visible light images, DUV images, computationally processed dual-band fusion images, and the temporal evolution of these images for four motion states of a rocket (upward acceleration, downward deceleration, leftward deceleration, and rightward acceleration). During the passage of the rocket, after the light stimulus is removed, the photocurrent gradually decays over time, and the photocurrent in the later frame is higher than that in the previous frame. Meanwhile, integrating the DUV band image information enables a clearer depiction of the rocket's trajectory.

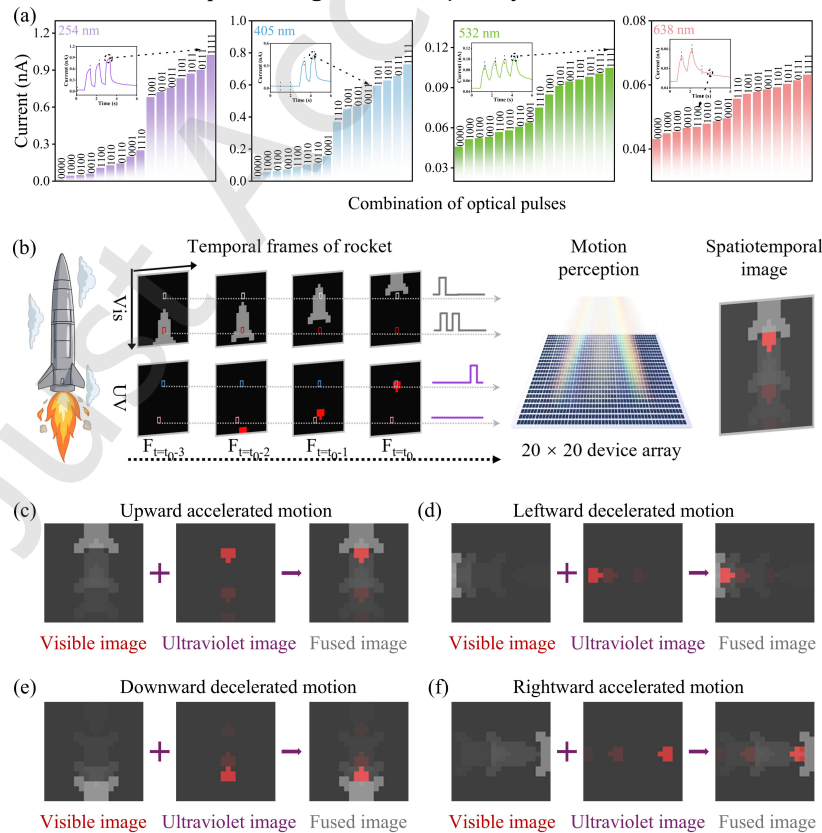


Figure 4. Action recognition based on tetrachromatic neuromorphic optoelectronic sensors and conventional image sensors. (a) Photoresponses to four-bit light stimulation under four-color light illumination. (b) Generation of dual-wavelength fused images by processing visible and ultraviolet spatiotemporal frames. Output current maps of visible, ultraviolet, and fused images for motion perception: (c) upward acceleration, (d) left deceleration, (e) downward deceleration, (f) right acceleration.

In real environments, numerous interfering factors exist. To simulate more realistic conditions, this study employs

neural network algorithms to process images, thereby achieving complex motion recognition of target objects in noisy images. Taking a rocket pattern as the target object, we assign eight spatiotemporal feature attributes and generate time-sequential frame images containing four rocket patterns. For the eight motion types (acceleration and deceleration in four directions), we constructed a dataset of 4,000 noisy images with Gaussian noise at a signal-to-noise ratio (SNR) of 0.5, using a 6:4 training-to-testing split.

Figure 5a illustrates the rocket trajectory motion recognition method based on a CNN combined with a fully connected neural network. The network takes a 100×100 -pixel composite image as input. Through two successive stages of convolution and max-pooling operations, the feature maps are progressively expanded to 32 channels with a spatial resolution of 25×25 . These feature maps are subsequently flattened into a 20000-dimensional vector and fed to 128 hidden-layer neurons. Subsequently, through the complex hierarchical processing of the fully connected neural network, six discriminant neurons are obtained at the output. Each neuron is specifically encoded to correspond to one of six different motion patterns. These six motion patterns can be divided into two categories: direction discrimination and speed discrimination. By combining the results of these two types of discrimination, the specific motion state of the object can be inferred. Four motion patterns are selected for display, as shown in Figure 5b, presenting (I) deep ultraviolet images, (II) visible light images, (III) fused images, and (IV) recognition images

obtained by a conventional sensor. A comparison reveals that the type I, II, and III images obtained in this study all contain four frames of temporal information, from which not only the direction of rocket motion can be determined but also the acceleration or deceleration state can be identified based on the distance difference between adjacent frames. Meanwhile, combining the deep ultraviolet and visible light images significantly improves the recognition accuracy. In contrast, the single-frame images generated by conventional sensors provide limited motion information and cannot support high-precision motion recognition.

The accuracy output by the neural network validates the effectiveness of the above experiments. Figure 5c shows the recognition accuracy for rocket motion direction. After 30 training epochs, the accuracy of the fused images reached 95.7%, significantly higher than that of the visible band (85.7%) and the deep ultraviolet band (79.6%). In comparison, the conventional sensor achieved the poorest recognition accuracy, only 67.1% (the corresponding confusion matrix is provided in Figure S10). The recognition accuracy for rocket speed follows the same trend (Figure 5d), with the fused images significantly outperforming the other cases (the corresponding confusion matrix is provided in Figure S11). These results demonstrate that dual-band information fusion can more fully capture spatiotemporal details and effective information during object motion, thereby significantly enhancing the accuracy of dynamic motion recognition and meeting the demands of dynamic recognition in complex scenarios.

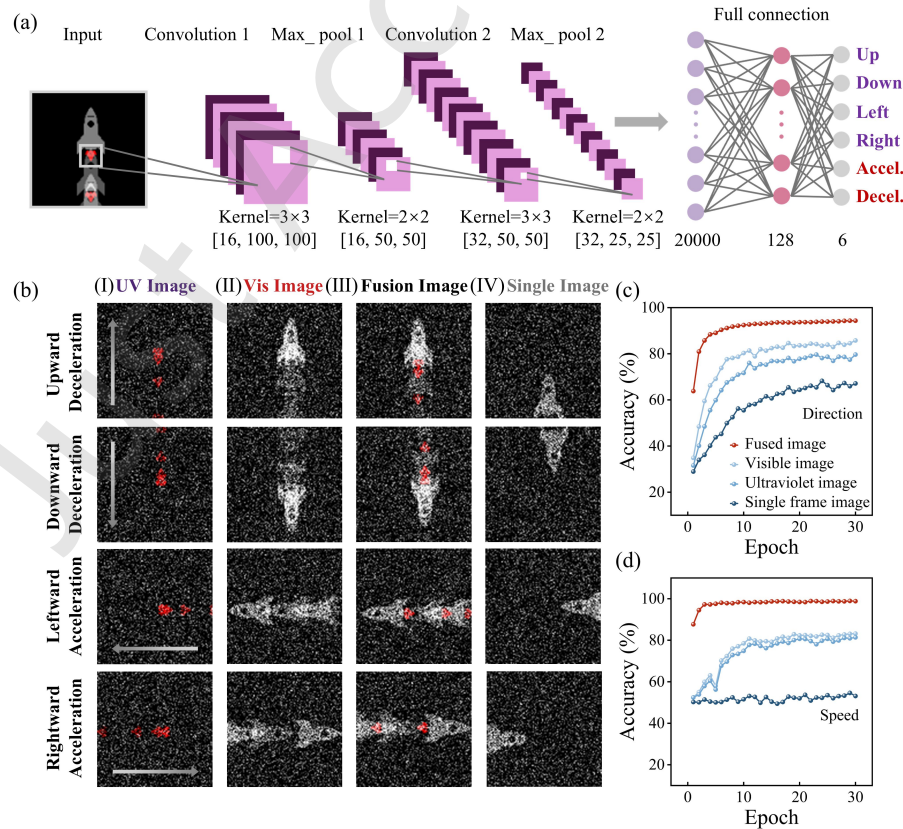


Figure 5. Motion recognition based on neural network computing. (a) Schematic of the motion recognition neural network based on fused images. The input consists of 100×100 pixel images. (b) (I) Spatiotemporal frame images acquired by an ultraviolet neuromorphic optoelectronic sensor, (II) spatiotemporal frame images acquired by a visible-light neuromorphic optoelectronic sensor, (III) image obtained from an image fusion sensor, (IV) single-frame image of a rocket captured by a conventional image sensor. Training-dependent evolution of recognition accuracy of the neuromorphic optoelectronic sensor for (c) motion direction, (d) acceleration.

3. Conclusion

In summary, inspired by the tetrachromatic vision of reindeer, this work presents a novel $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensor capable of responding to four distinct wavelengths (254, 405, 532 and 638 nm). By utilizing the defect-rich TiO_2 formed via oxidation of MXene to construct a Type-II heterojunction with Ga_2O_3 , broadband light modulation and conductance plasticity are achieved. On this basis, we demonstrate a dual-band (ultraviolet and visible) fusion perception system based on a 20×20 sensor array, which further enables the synchronous encoding and processing of spatiotemporal motion information through in-sensor computing. By combining in-sensor computing with neural network algorithms, the system achieves a high motion recognition accuracy of 95.7% for complex trajectories (e.g., acceleration/deceleration in four directions). This study not only provides a feasible material strategy for broadband neuromorphic photodetection but also establishes a new paradigm for high-precision dynamic vision in complex environments.

4. Experimental Section/Methods

Materials and Reagents: The Ti_3AlC_2 MAX-phase precursor used in this study was obtained from Jilin Yiyi Technology Co., Ltd. Hydrochloric acid (HCl, 9 M) and lithium fluoride (LiF) were purchased from Aladdin Co., Ltd.

Preparation and Oxidation Control of Ti_3AlC_2 MXene: An in-situ HF etching solution was prepared by dissolving 1.6 g of LiF in of 9 M HCl and deionized water. Subsequently, 1 g of Ti_3AlC_2 MAX-phase powder was slowly added to the etchant and allowed to react in an oil bath at 35°C for 24 hours. The resulting product was thoroughly washed with deionized water and centrifuged to obtain multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. The collected precipitate was then subjected to ultrasonic intercalation in a water bath for 1 hour. Following a final centrifugation step, the supernatant containing the single-layer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene aqueous dispersion was collected.

Oxidation Control: Under continuous stirring, the as-prepared monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene dispersion was placed on a heating block set to 60°C , with the ambient relative humidity maintained at 25%. By precisely controlling the heating duration, partial oxidation was induced to form an in-situ defect-rich TiO_2 layer on the MXene, ultimately yielding the desired $\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ composite solution.

Preparation of $\beta\text{-Ga}_2\text{O}_3$ Films: High-quality $\beta\text{-Ga}_2\text{O}_3$ films were epitaxially grown on sapphire (Al_2O_3) substrates using metal-organic chemical vapor deposition (MOCVD). Prior to growth, the sapphire substrates were sequentially cleaned by ultrasonication in acetone, ethanol, and deionized water for 10 minutes each, and subsequently dried under a nitrogen stream. Using triethylgallium as the gallium precursor, O_2 as the reactant gas, and Ar as the carrier gas, the deposition was conducted at a growth temperature of 830°C and a chamber pressure of 60 torr, producing a dense $\beta\text{-Ga}_2\text{O}_3$ film.

Device Fabrication and Measurements: A $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ tetrachromatic optoelectronic sensor was fabricated on a sapphire substrate and patterned into a 20×20 array via photolithography. The array was defined using a maskless lithography system (MLA100, Heidelberg

Instruments). Specifically, a photoresist (AZ5214) film was spin-coated onto the Ga_2O_3 sapphire substrate at 3000 rpm for 40 s, followed by soft baking on a hot plate at 100°C for 1.5 min. The predefined pattern was then exposed using a mask aligner. After development, the prepared $\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$ dispersion was spray-coated onto the patterned film, dried at 100°C , and lift-off was performed. A second photolithography step was subsequently employed to define the electrode patterns, followed by thermal evaporation of a 50 nm Ag film to complete the device fabrication. The electrical and optoelectronic characteristics of the devices were measured in vacuum at room temperature using a semiconductor parameter analyzer (Keithley 2636A) integrated with a probe station (TTPX, Lake Shore). Synaptic behaviors were excited using pulsed light sources with wavelengths of 254 nm, 405 nm, 532 nm and 638 nm.

Electronic Supplementary Material: Supplementary material (additional experimental and calculation details) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909170>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request."

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

L.X.M. and J.S.Y. contribute equally to this work. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Use of AI statement

None

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Electronic Supplementary Material

Tetrachromatic-inspired neuromorphic optoelectronic sensor based on $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ heterostructures for dual-band dynamic motion perception

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1. Supplementary Figures

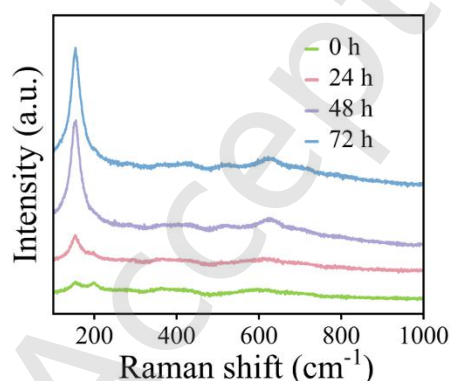


Figure S1. Raman spectra of MXene under different oxidation times.

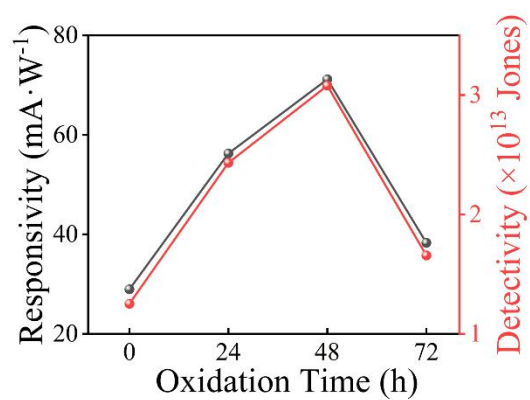


Figure S2. Responsivity and detectivity of $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ photosensors based on $\text{Ti}_3\text{C}_2\text{T}_x$ with different oxidation times (0, 24, 48 and 72 h).

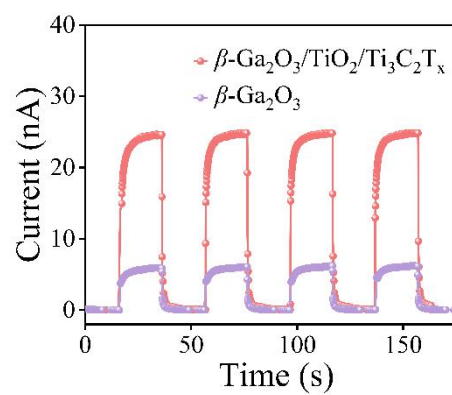


Figure S3. I-t curves of pristine Ga_2O_3 device and $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device.

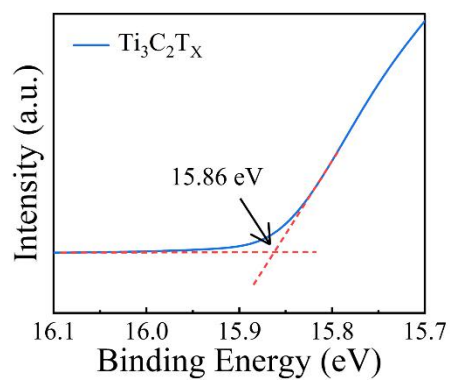


Figure S4. The work function of $\text{Ti}_3\text{C}_2\text{T}_x$ can be determined from the secondary electron cutoff edge measured by UPS.

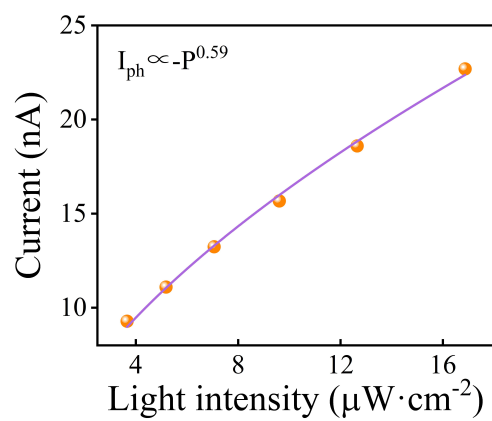


Figure S5. I–P characteristics under bias voltages of 10 V.

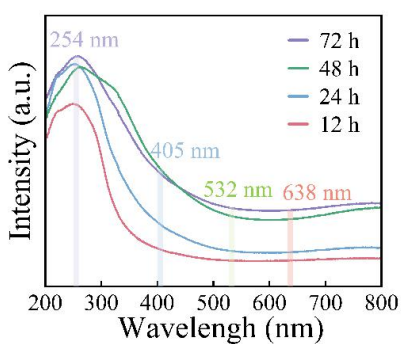


Figure S6. UV-Vis absorption spectra of $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ with different oxidation times.

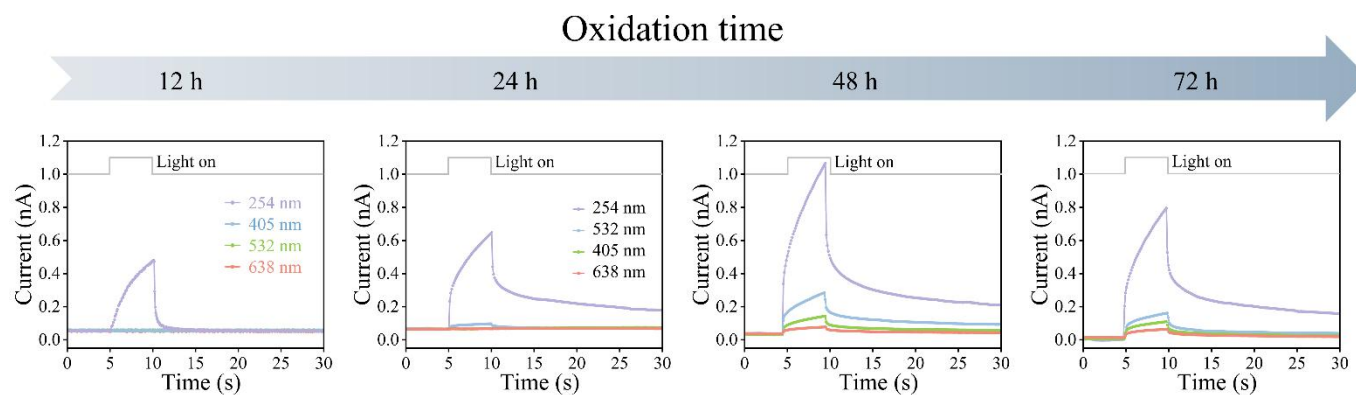


Figure S7. Photoresponse currents of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ neuromorphic optoelectronic sensor with different oxidation times under 254, 405, 532 and 638 nm illumination.

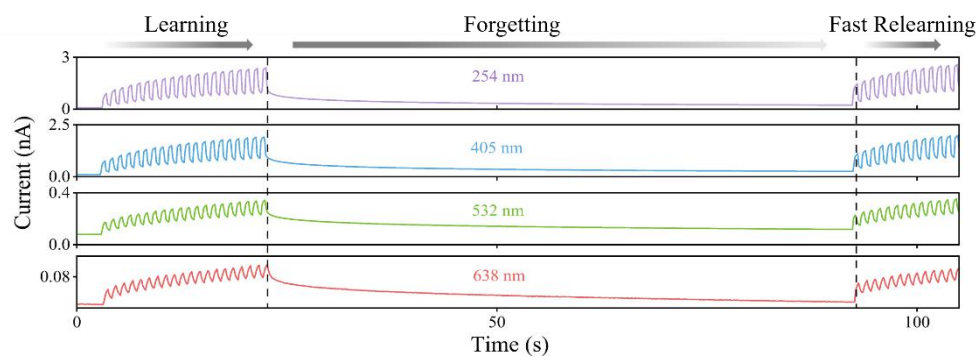


Figure S8. Learning, forgetting, and relearning characteristics of the $\text{Ga}_2\text{O}_3/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ device under 254, 405, 532 and 638 nm wavelength light.

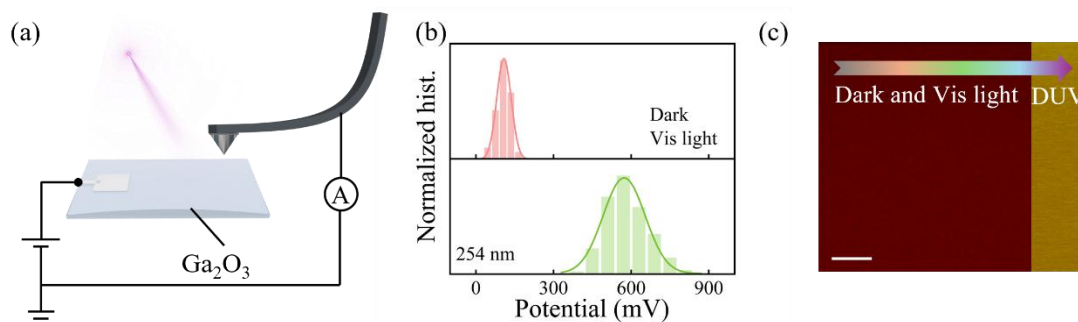


Figure S9. (a) Schematic diagram of in situ KPFM measurement of the surface potential of a Ga_2O_3 film. (b) Surface potential distribution of the Ga_2O_3 composite film under four-color light irradiation. (c) Surface potential difference histogram of the Ga_2O_3 composite film under four-color light irradiation.

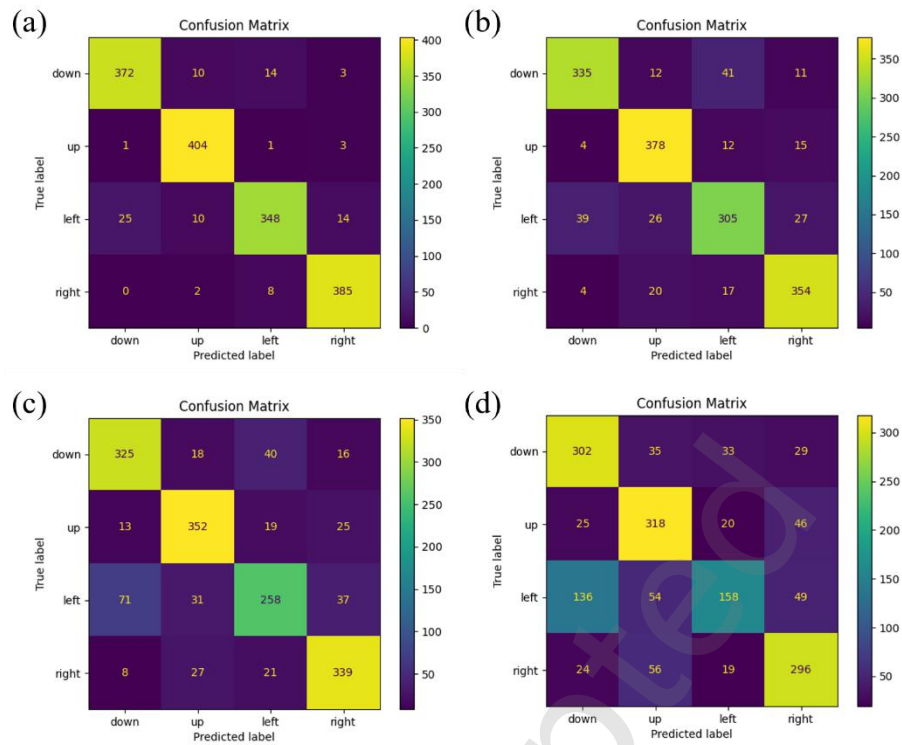


Figure S10. (a) Output confusion matrices of the image fusion sensor, (b) visible-light vision sensor, (c) ultraviolet vision sensor, and (d) conventional vision sensor, respectively showing the classification results for motion directions (up, down, left, right).

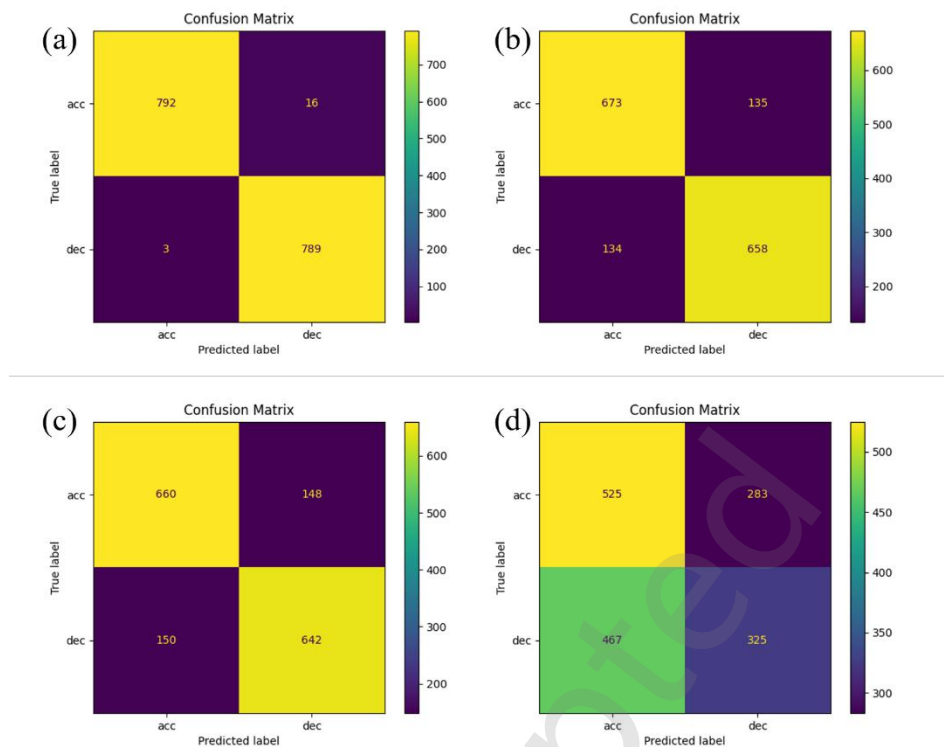


Figure S11. (a) Output confusion matrices of the image fusion sensor, (b) visible-light vision sensor, (c) ultraviolet vision sensor, and (d) conventional vision sensor, respectively showing the classification results for motion acceleration (acceleration/deceleration).

Table S1 Comparison of material systems, response band, PPF index, synaptic functions, responsivity, and recognition accuracy between previously reported neuromorphic optoelectronic devices and this work.

Memristive materials	Response Band	PPF A_2/A_1	Synaptic Functions	Responsivity (mA/W)	Recognition Accuracy	Ref.
p-GaN/n-AlGaIn/n-GaN	265 nm	1.22	EPSC, PPF	10.45	95% (FMNIST)	1
TiO ₂ /IGZO	625/520/470 nm	2	STM/LTM, PPF	/	90.3% (MNIST)	2
Si-doped β -Ga ₂ O ₃ /ZnO	255/370 nm	1.47	PPF, EPSC/IPSC	/	95.5% (MNIST)	3
MoS ₂ / β -Ga ₂ O ₃ /MLG	254/405 nm	Up to 1.6	STP, PPF, LTP, LTD	/	91.07% (CIFAR-10)	4
ITO/amorphous Ga ₂ O ₃ /Al	242 nm	Up to 1.36	PPF, LTP/LTD	14.23	93% (NVS)	5
ITZO/Ga ₂ O ₃	275/365/470/550 nm	Up to 1.25	PPF, PPD, LTP, LTD	/	97.13% (MNIST)	6
Ag/Ga ₂ O ₃ /Pt	254/365 nm	1.27	PPF, SIDP, SNDP, STDP, SFDP, SRDP, STM, LTM,	/	90.7% (MNIST)	7
MoS ₂ /h-BN/ α -In ₂ Se ₃ /h-BN	365–637 nm	/	PPC and NPC	/	96.5% (Dynamic facial expression recognition)	8
PdSe ₂ /pentacene	MIR	1.93	EPSC, PPF, LTP	/	95.7% (motion recognize)	9
graphdiyne/MoS ₂	430–633 nm	Up to 2	EPSC, PPF, PPD, SNDP, SRDP	/	95.46% (motion recognize)	10
Ga ₂ O ₃ /TiO ₂ /Ti ₃ C ₂ T _x	254–638 nm	1.5	EPSC, PPF, SRDP	128	95.7% (motion recognize)	This work.

Reference

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