

Two-dimensional optoelectronic neuromorphic hardware for visual in-sensor computing: Mechanisms, integration, and event-driven perception

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Nano Res., **Just Accepted Manuscript** • <https://doi.org/10.26599/NR.2026.94909216>

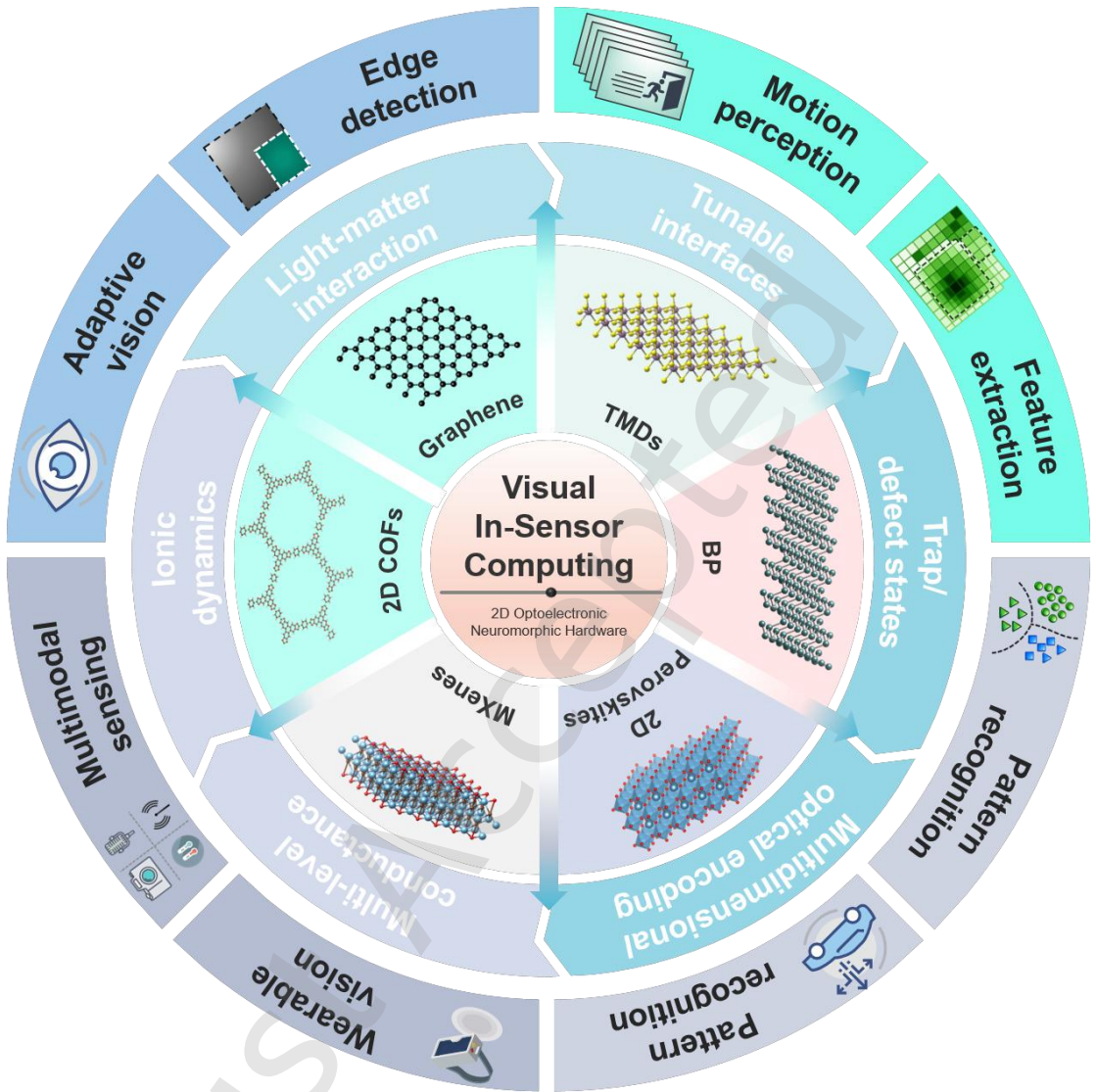
<https://www.sciopen.com/journal/1998-0124> on Sep. 24, 2026

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TABLE OF CONTENTS (TOC)



This review presents a cross-scale framework linking 2D materials, optoelectronic properties, neuromorphic responses, and visual ISC tasks. It highlights the relationships between material characteristics, device functions, and visual applications. This framework guides material selection, device design, and system integration for visual ISC.

Review Article

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Received: 15 July 2026; **Revised:** 25 August 2026; **Accepted:** 24 September 2026

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Cite this article: *Nano Research*, 2026, 19, 94909216 <https://doi.org/10.26599/NR.2026.94909216>

ABSTRACT: Visual in-sensor computing (ISC) provides a promising route for reducing redundant data transfer and enabling low-power visual intelligence at the sensor front end. Two-dimensional (2D) material-enabled optoelectronic neuromorphic devices are well suited for this paradigm because their light-matter interaction, tunable interfaces, defect states, ionic dynamics, and anisotropic responses can couple optical sensing with conductance modulation and memory. However, the field is still dominated by diverse material systems, isolated device demonstrations, and application-specific reports. A clear framework is needed to connect material properties, photoinduced mechanisms, device architectures, array integration, and visual ISC functions. In this review, recent progress in 2D optoelectronic neuromorphic devices is reorganized from this cross-scale perspective. The discussion highlights how 2D and quasi-2D material platforms enable light-induced synaptic plasticity, how different device architectures translate these mechanisms into programmable conductance states, and how array-level systems support visual preprocessing, dynamic perception, multidimensional encoding, and pattern recognition. Particular attention is given to the transition from single-device proof-of-concept studies to array-level and task-level visual ISC. Key challenges are further analyzed, including material nonuniformity, device drift, array variability,

readout noise, limited benchmarking, and insufficient real-scene validation. This review aims to clarify the development path of 2D optoelectronic neuromorphic hardware toward scalable, reliable, and energy-efficient visual ISC systems.

KEYWORDS: two-dimensional materials, optoelectronic neuromorphic devices, visual in-sensor computing, synaptic plasticity, artificial visual systems

1 Introduction

The rapid growth of artificial intelligence has placed increasing demands on visual sensing systems [1-4]. Modern visual systems are expected to process large amounts of spatial, temporal, and spectral information in real time [5, 6]. However, traditional machine vision architectures struggle to meet these growing demands [7-9]. In traditional machine vision, optical sensing, signal conversion, memory access, and digital computation are typically performed by separate hardware units [9]. Such a separated pipeline causes frequent data transfer between sensors, memories, and processors. It also increases latency and energy consumption. These problems become more serious in edge-vision scenarios, where devices must operate under limited power budgets and respond to dynamic scenes [10, 11]. Typical examples include autonomous navigation, robotic perception, wearable vision, and environmental monitoring [12-15]. In these tasks, the sensor must not only record images, but also extract useful features from motion, noise, changing illumination, and complex backgrounds. Visual in-sensor computing (ISC) provides a promising route to address these challenges [16-18]. By integrating sensing, memory, and early-stage processing within the sensor front end, visual ISC can reduce redundant data movement [19, 20]. It also enables local encoding, filtering, and compression of optical information before downstream computation [21, 22].

Biological vision provides a useful model for this front-end computing strategy. The retina is not only an optical receptor but also performs preliminary visual processing before the information is transmitted to the brain [23, 24]. Photoreceptors

convert light into electrical signals [25]. Bipolar cells and local neural circuits regulate contrast and signal flow [26]. Ganglion cells encode spatiotemporal visual information and transmit it to higher visual centers [27]. The hierarchical pathways of the visual system support adaptation, edge enhancement, motion sensitivity, parallel processing, and temporal coding [6, 28]. These features are closely related to the requirements of visual ISC and indicate that useful visual features should be generated at the sensing front end rather than after full-frame transfer [29, 30]. Fig. 1 summarizes the cross-scale framework of 2D optoelectronic neuromorphic hardware for visual ISC. The retina provides the biological reference by integrating light sensing, local preprocessing, spatiotemporal encoding, and selective signal transmission before visual information reaches the brain [24, 31]. Inspired by this processing strategy, representative 2D material platforms provide the physical basis for coupling optical excitation with charge transport and memory effects [32, 33]. Their key characteristics include strong light-matter interaction, tunable band structures and interfaces, defect and trap states, ionic dynamics, and anisotropic photoresponse. These characteristics can be translated into device-level functions through optoelectronic synapses, optoelectronic memristors, and heterojunction synaptic transistors [34, 35]. Representative functions include optical sensing, temporal memory, multilevel conductance modulation, and multidimensional optical encoding. When further integrated into pixel and array architectures, these functions support sensing, memory, and computation at the visual front end [36-38]. They enable visual preprocessing tasks such as edge detection, motion perception, and feature extraction, and can further support autonomous driving, wearable vision, and multimodal sensing [39]. Recent studies have also demonstrated adaptive photoresponse and reconfigurable visual processing under complex illumination conditions [40]. Tunable temporal dynamics further provide a basis for multi-timescale visual information processing [41].

Owing to their reduced dimensionality and rich interfacial physics, 2D materials

provide a useful materials basis for optoelectronic neuromorphic devices in visual ISC [42-44]. Many 2D and quasi-2D materials exhibit strong light-matter interaction, tunable electronic structures, and interface sensitive charge transport [45, 46]. These properties allow optical inputs to be converted into photocurrent, conductance modulation, and memory states. Defect and trap states can prolong the lifetime of photogenerated carriers [47]. Van der Waals interfaces can promote charge transfer and photogating effects [48]. Ion migration and ferroelectric polarization can further regulate channel conductance [49]. In low symmetry materials, anisotropic transport and polarization sensitive photoresponse offer additional degrees of freedom for visual information encoding [50]. As a result, optical intensity, wavelength, temporal sequence, and polarization can be used not only as stimulus parameters, but also as information dimensions for visual ISC. This review covers representative studies from the early development of 2D optoelectronics to recent advances reported up to 2026. In this review, the primary scope is restricted to optoelectronic neuromorphic systems in which 2D materials serve as the active or functionally dominant component. Quasi-2D, mixed-dimensional, and hybrid systems are discussed separately as related extensions when their low-dimensional interfaces or coupled components provide mechanisms relevant to visual ISC. In addition, a limited number of non-2D devices are included only as benchmark or structural reference cases and are not treated as core 2D material platforms. These systems are considered when their optical response, memory effect, or interfacial modulation directly contributes to optoelectronic neuromorphic devices or visual ISC. Although 2D materials provide important opportunities for visual ISC, several issues remain unresolved [51, 52]. Many reported devices exhibit typical synaptic behaviors, including excitatory postsynaptic current (EPSC), paired-pulse facilitation (PPF), short-term plasticity (STP), and long-term plasticity (LTP) [53-55]. These results are useful for validating device-level plasticity. However, they do not necessarily demonstrate whether the devices can support array-level computing or practical visual tasks. Similar synaptic responses may also

originate from different physical mechanisms. Photogating, persistent photoconductivity, ion migration, and ferroelectric modulation can all induce memory-related conductance changes [56-58]. However, these mechanisms differ in response speed, retention time, reversibility, stability, energy consumption, and scalability [59]. Such differences determine whether a device is more suitable for fast optical sensing, temporal integration, nonvolatile weight storage, or array-level visual preprocessing [60-62]. Therefore, a summary based solely on material systems is insufficient for evaluating this field. It is important to clarify how 2D material properties produce light-induced plasticity, how such plasticity is implemented in device architectures, and how these devices operate in arrays for visual tasks [63]. This materials mechanisms devices arrays framework can help assess the transition from single device demonstrations to practical visual ISC systems.

This review focuses on 2D material-enabled optoelectronic neuromorphic devices for visual ISC. Building on previous reviews of 2D optoelectronic materials, neuromorphic devices, and artificial visual systems, we adopt a cross-scale and task-oriented perspective that connects materials, mechanisms, devices, arrays, and visual functions. Particular emphasis is placed on matching material and device characteristics with task-specific requirements and on the transition from single-device demonstrations to array-level and system-level visual computing. Representative 2D and quasi-2D materials are discussed in terms of their optical response, interface tunability, memory-related dynamics, and integration potential. The underlying light-induced mechanisms are analyzed to explain how optical inputs are converted into synaptic plasticity, conductance modulation, and memory states. Device architectures and light-regulated synaptic behaviors are examined as links between material responses and neuromorphic functions. The discussion further extends to pixel arrays, front-end computing circuits, and visual ISC tasks. Remaining challenges are addressed from the perspectives of material uniformity, device drift, array variability, readout noise, benchmarking, and hardware-algorithm co-design. By

linking material physics with device operation and system-level visual functions, this review aims to clarify the development path toward practical, scalable, and energy-efficient 2D optoelectronic visual ISC systems.

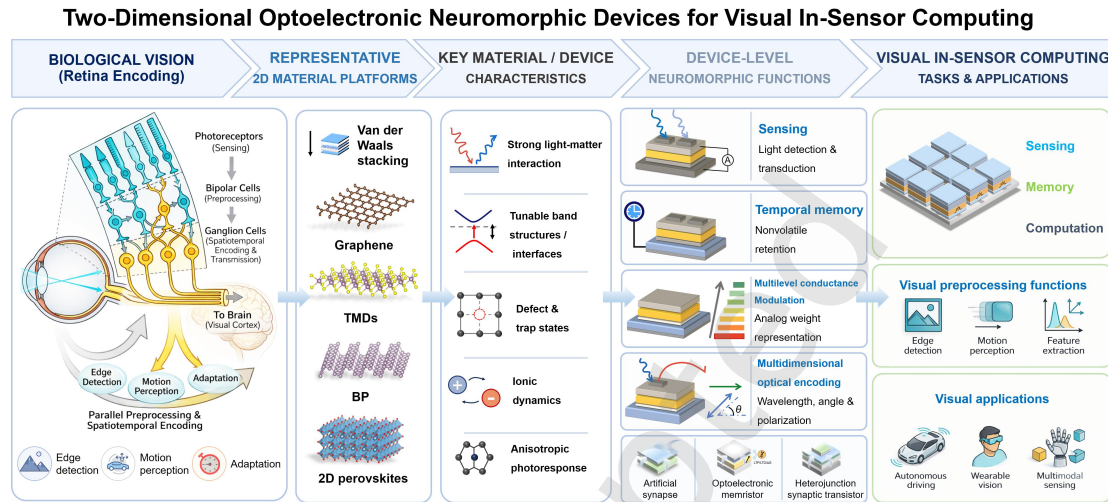


Figure. 1 Conceptual framework of 2D optoelectronic neuromorphic devices for visual ISC.

2 Material Platforms and Optoelectronic Advantages

The development of visual ISC depends strongly on the active materials used in optoelectronic neuromorphic devices [64]. In conventional photodetectors, materials mainly determine optical absorption and charge transport. In neuromorphic visual hardware, the role of materials is broader [65]. They need to support light detection, conductance regulation, memory formation, and repeatable state modulation. 2D material-enabled systems are well suited for this purpose because their reduced dimensionality makes optical, electrical, and interfacial processes highly tunable. Thickness, defects, surface states, van der Waals interfaces, ionic motion, and polarization effects can all affect the device response [66]. These material features provide the physical basis for converting optical inputs into synaptic plasticity and visual computing functions.

2.1 Evolution from 2D Materials to Visual ISC

The development of 2D optoelectronic neuromorphic vision has progressed from

material exploration to device functions and visual ISC. Early studies mainly focused on the optoelectronic properties of 2D semiconductors [67]. Monolayer and few-layer 2D materials showed thickness-dependent band structures, efficient light absorption, and sensitive surface transport. These properties made them attractive for photodetectors, field-effect transistors, and light-sensitive electronic devices. At this stage, the main goal was to understand how 2D materials convert optical inputs into electrical signals.

As summarized in Fig. 2, the field gradually moved beyond conventional photodetection. Direct-gap monolayer MoS₂ optoelectronics established an important material basis for 2D light-sensitive devices [68]. Wafer-scale growth of uniform 2D semiconductor films further improved the possibility of large-area device fabrication [69]. These advances provided the foundation for later neuromorphic functions. With the emergence of light-tunable optoelectronic synapses, optical inputs were no longer treated only as signals to be detected [70]. They were also used to regulate conductance, induce synaptic plasticity, and form memory states.

The material scope also expanded during this evolution. Early demonstrations were mainly based on typical transition metal dichalcogenides. Later studies introduced broader material systems, such as TiS₃ and other layered semiconductors, black phosphorus, 2D perovskites, MXenes, framework materials, and hybrid heterostructures [71]. This expansion was driven by the need for richer optical and memory functions. Different material systems offer different advantages. Some provide broadband photoresponse. Some show strong anisotropy or polarization sensitivity. Others support ion-mediated modulation, interfacial charge transfer, or molecular-level design. These material degrees of freedom helped transform 2D optoelectronic devices from simple light-responsive components into programmable synaptic units [72]. Recent progress has further shifted the field toward array-level visual processing and scalable integration. ANN-assisted imaging arrays have shown that sensor outputs can be calibrated and recovered through hardware-software

cooperation [73]. Interface-engineered 2D heterostructure photo-synapses have enabled multilevel plasticity and more controllable memory behavior [74]. Large-scale visual synaptic arrays have demonstrated image recognition and front-end preprocessing [75]. Integration-compatible 2D synaptic kernels have also started to connect material-level device functions with circuit-level implementation [76]. These advances indicate that the key question is changing. It is no longer only whether a single device can mimic synaptic behavior. It is also whether the device can operate reliably in arrays and support visual computing tasks [77].

This evolution highlights the role of materials in determining the direction of visual ISC. Strong light absorption supports optical sensing. Defects and interfaces provide memory and plasticity. Anisotropic structures enable polarization-sensitive encoding. Ionic and ferroelectric effects offer routes for nonvolatile modulation. Therefore, the transition from 2D materials to visual ISC is not a simple increase in device complexity. It requires coordinated design across materials, mechanisms, devices, arrays, and algorithms. This view provides the basis for discussing representative 2D-material-enabled platforms and their optoelectronic advantages.

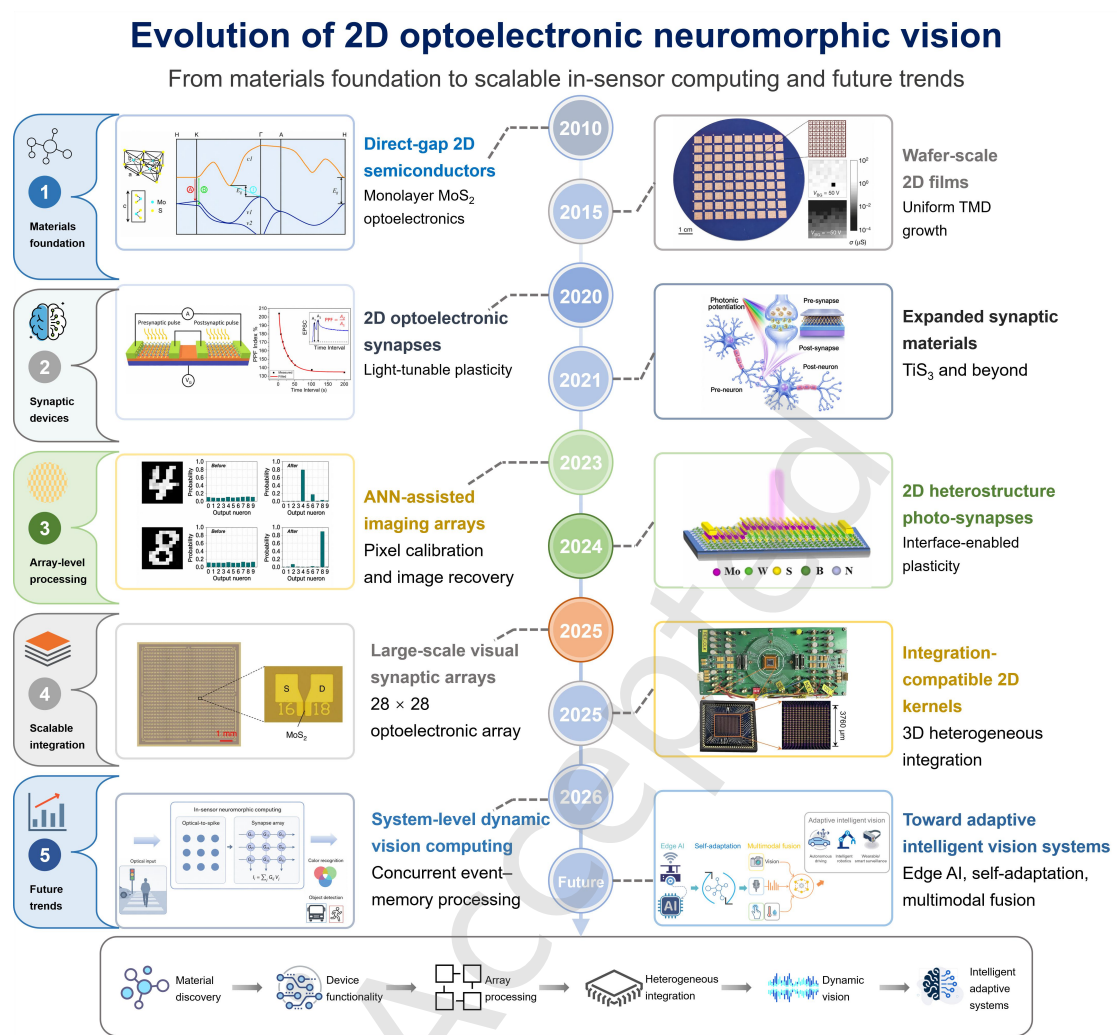


Figure 2 The timeline summarizes the transition of 2D optoelectronic neuromorphic vision from material discovery to device functionality, array-level preprocessing, scalable integration, and future intelligent systems. Early studies established the optoelectronic basis of 2D semiconductors and wafer-scale 2D films [68, 69]. Copyright 2010, American Physical Society; Copyright 2015, Springer Nature. Subsequent advances introduced light-tunable optoelectronic synapses and expanded the material systems beyond conventional TMDs [70, 71]. Copyright 2020, Islam, M.M. et al; Copyright 2021, American Chemical Society. Recent progress has further moved toward ANN-assisted imaging arrays [73], Copyright 2022, Lee, D. et al. interface-engineered heterostructure photo-synapses [74], Copyright 2024, Elsevier. large-scale visual synaptic arrays [75], Copyright 2025, Zhang, F. et al. and integration-compatible 2D synaptic kernels [76, 77]. Copyright 2025, He, Q. et al; Copyright 2026, Wang, J. et al. Future development is expected to focus on dynamic visual ISC, edge

intelligence, self-adaptive perception, and multimodal fusion.

2.2 Representative 2D-material-enabled platforms

For clarity, the material platforms discussed here are grouped according to their dimensionality and functional role in the device. Graphene, TMDs, and BP are treated as representative intrinsic or layered 2D materials. Layered perovskites, MXenes, and framework-based materials are discussed as broader low-dimensional or quasi-2D platforms where appropriate. Mixed-dimensional and hybrid heterostructures are considered separately. These systems are included when a 2D component plays a dominant role in optical response, charge modulation, or memory formation. Fig. 3(a) summarizes representative 2D and quasi-2D material platforms for optoelectronic neuromorphic devices. These platforms include graphene, transition metal dichalcogenides, black phosphorus, 2D perovskites, MXenes, and 2D covalent organic frameworks or hybrid materials. These materials are not selected only because of their low-dimensional structures. More importantly, they provide different physical routes for optical sensing, conductance modulation, memory formation, and visual information encoding.

Graphene has broadband optical absorption, high carrier mobility, and excellent electrical conductivity [78]. These properties make it useful as a transparent electrode, transport channel, or floating gate layer. However, pristine graphene lacks an intrinsic bandgap. It is therefore often combined with semiconducting 2D materials or dielectric layers to improve light response and charge storage. These characteristics make graphene particularly useful for broadband optical coupling and rapid carrier transport in hybrid visual devices. Its lack of an intrinsic bandgap limits spectral selectivity and standalone memory functions. TMDs, such as MoS₂, WS₂, WSe₂, and MoSe₂, provide tunable bandgaps and strong photoresponse [79]. Their atomically thin channels are sensitive to gate fields, defects, adsorbates, and interfacial charge transfer. These features make TMDs widely used in phototransistors, optoelectronic

synapses, and van der Waals (vdW) heterojunction devices. Their tunable band structures and interface-sensitive transport are well suited for wavelength-selective sensing, gate-controlled photoresponse, and programmable synaptic weighting. BP provides a different advantage [80]. It has a thickness-dependent bandgap, broadband optical response, and strong in-plane anisotropy. These properties make BP particularly suitable for polarization-sensitive and orientation-resolved visual perception. Its main limitation is environmental instability, which requires encapsulation or interface protection. 2D perovskites show strong optical absorption, long carrier lifetime, and rich defect or ion-related dynamics [81]. Their strong optical absorption and long-lived carrier or ion-related dynamics favor temporal integration, synaptic memory, and memory-assisted image preprocessing. Their solution processability is also attractive for large-area and flexible devices, although stability and ion-migration-induced drift remain concerns.

MXenes have high conductivity and abundant surface terminations. They can support ion interaction, surface charge regulation, and mixed ionic-electronic transport. These features are useful for flexible and multifunctional optoelectronic synapses [79]. These properties favor low-voltage conductance modulation and adaptive synaptic weighting, especially in flexible or ion-coupled visual hardware. 2D COFs and related hybrid materials provide molecular-level designability. Their pore structures, conjugated skeletons, and functional groups can be tailored for optical absorption, charge transport, and ion interaction [82]. Their molecular tunability provides a useful route for programmable optical response, multilevel memory, and low-power visual information storage. Overall, these material platforms provide complementary routes for different visual functions. TMDs are well suited for wavelength-selective sensing and gate-tunable synaptic modulation. BP is advantageous for polarization- and orientation-sensitive vision. 2D perovskites favor temporal integration and memory-assisted preprocessing. MXenes support ion-coupled conductance modulation and adaptive weighting. Framework-based

materials provide molecular tunability for low-power memory and multilevel information storage. Hybrid heterostructures further enable multifunctional optical encoding through interface engineering.

2.3 Material advantages for visual ISC

Fig. 3(b) highlights the key optoelectronic advantages of 2D material-enabled systems for visual ISC. These advantages include strong light-matter interaction, tunable bandgap and broadband response, trap-rich interfaces, vdW heterojunction engineering, and polarization-sensitive photoresponse. They determine how optical signals are detected, stored, and processed in neuromorphic visual hardware.

Strong light-matter interaction is the basis of optical sensing [83]. In many 2D and quasi-2D semiconductors, reduced dimensionality enhances excitonic effects and makes the electronic states sensitive to optical excitation. This allows incident light to generate photocurrent or conductance changes in compact devices. Tunable band structures provide another important advantage. The bandgap and spectral response can be regulated by layer number, strain, electric field, chemical composition, or heterostructure design [84]. This enables broadband sensing and wavelength-selective encoding. Trap-rich interfaces play a central role in optoelectronic neuromorphic behavior [85]. In conventional electronics, defects and traps are often treated as sources of instability. In neuromorphic devices, controlled trapping can be useful. Trapped photocarriers can modulate the local electric field and maintain conductance changes after illumination. This process supports short-term memory, long-term memory, and temporal integration. The key challenge is to control trap density and relaxation dynamics, rather than relying on random disorder. vdW heterojunction engineering offers a flexible route for interface design [86]. Different 2D materials can be stacked without strict lattice matching. This allows regulation of band alignment, built-in electric fields, tunneling barriers, and charge storage layers. Such interfaces can promote charge separation, photogating, and persistent conductance

modulation. Low-symmetry 2D materials further provide polarization-sensitive photoresponse [87]. This allows polarization and orientation information to be encoded at the device level. These advantages make 2D materials suitable for multidimensional visual ISC, where intensity, wavelength, time, and polarization can all serve as information channels.

2.4 Material-function relationship

Material advantages refer to the intrinsic or interface-dependent properties of the material platform, including optical absorption, band structure, trap states, ionic dynamics, and anisotropy. Device functionality describes the operations generated after these properties are coupled with device geometry, electrodes, interfaces, and external stimuli. Representative functions include optical sensing, temporal memory, multilevel conductance modulation, spectral selectivity, and visual preprocessing. The material-specific trends discussed above can be further generalized into a property-function relationship for visual ISC. Fig. 3(c) connects the material features of 2D systems with representative visual ISC functions. These functions include optical sensing, synaptic memory, multi-level conductance modulation, visual preprocessing, multidimensional optical encoding, and pattern recognition. The relationship is not a simple one-to-one mapping. A single material property may contribute to several device functions. A single device function may also require multiple physical processes.

Optical sensing is the most basic function. Strong optical absorption and efficient carrier generation allow 2D materials to convert light into electrical signals. This provides the first step for visual ISC [88]. Synaptic memory is enabled by carrier trapping, interfacial charge storage, ion migration, or ferroelectric polarization [89]. These processes allow the device state to retain information after optical stimulation. As a result, the device can record part of the optical history and support temporal integration. Multilevel conductance modulation provides the basis for analog weight

storage. Light pulses can gradually change the device conductance. These conductance states can represent synaptic weights or optical memory states. This function is important for in-sensor learning and feature weighting. Visual preprocessing relies on the dynamic response of the device [90]. Temporal relaxation, persistent photoconductivity, and nonlinear conductance modulation can help enhance contrast, suppress noise, or extract edges. These operations reduce redundant data before downstream computation.

Multidimensional optical encoding is enabled by the sensitivity of 2D materials to light intensity, wavelength, time, and polarization. These dimensions allow richer visual information to be encoded at the sensor front end. Pattern recognition usually requires the integration of material response, device plasticity, array operation, and algorithms [91]. In this process, 2D material-enabled devices provide sensing and preprocessing functions, while neural networks or machine learning models complete classification or decision-making. Therefore, material selection should be guided by the target visual ISC function. Fast photoconductive materials are suitable for real-time sensing. Trap-rich materials are useful for temporal memory. Anisotropic materials are suitable for polarization-sensitive vision. Hybrid heterostructures are suitable for multifunctional encoding and multilevel synaptic modulation.

To further support the material-function relationship discussed above, Table 1 summarizes representative performance metrics of several 2D-material-enabled platforms for visual ISC. The reported values were obtained under different illumination wavelengths, optical powers, bias conditions, pulse parameters, and task settings. Their specific testing conditions are provided in the corresponding original studies. The comparison focuses on general performance trends and material-function relationships across different platforms. These examples show that different material systems contribute to distinct visual functions. TMD heterostructures are suitable for wavelength-dependent sensing and recognition, while defect-engineered 2D semiconductors provide long retention and low-energy temporal memory. Anisotropic

2D materials enable polarization-sensitive vision, and 2D perovskites are useful for image preprocessing through persistent photoresponse and low-energy operation. In contrast, 2D framework materials show promise for low-power memory and multilevel information storage. These comparisons indicate that the selection of materials should be guided by the target ISC function, rather than based solely on the novelty of the material.

In summary, the suitability of a material platform for visual ISC is determined by the physical processes required by the target task. Strong optical coupling and rapid carrier transport favor fast sensing. Controlled trapping and ionic dynamics support temporal integration and memory. Tunable band structures and interfaces enable spectral selectivity, and anisotropic materials provide polarization-sensitive encoding. Material selection should therefore be guided by the required balance among sensing speed, memory, selectivity, stability, and integration compatibility.

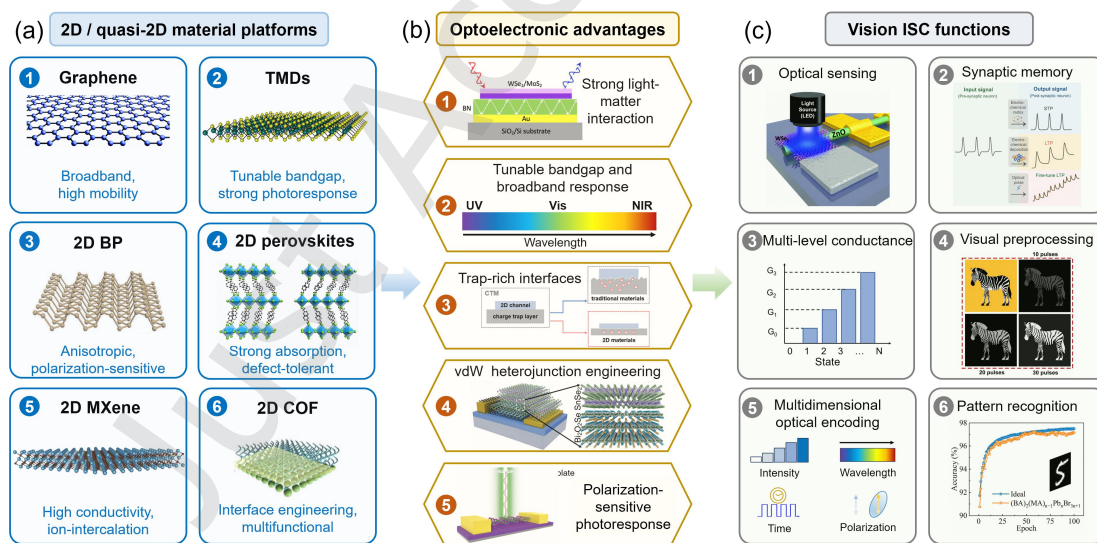


Figure 3. Representative 2D/quasi-2D material platforms, optoelectronic advantages, and visual ISC functions. (a) Typical material platforms, including graphene, TMDs, BP, 2D perovskites, MXenes, and 2D COF [78-82]. Copyright 2011; American Physical Society. Copyright 2024, Royal Society of Chemistry; Copyright 2017, Wiley-VCH; Copyright 2019, American Chemical Society; Copyright 2023, Wiley-VCH. (b) Key optoelectronic advantages of 2D systems, including strong light-matter interaction, tunable bandgap and broadband

response, defect/trap-mediated memory, van der Waals heterostructure engineering, and polarization-sensitive photoresponse [83-87]. Copyright 2019, Elsevier; Copyright 2017, American Chemical Society; Copyright 2024, Wiley-VCH; Copyright 2016, Wiley-VCH. (c) Representative visual ISC functions enabled by these material and device features, including optical sensing, synaptic memory, multilevel conductance modulation, visual preprocessing, multidimensional optical encoding, and pattern recognition [88-91]. Copyright 2023, Wang, Y. et al.; Copyright 2017, Wiley-VCH; Copyright 2024, Wiley-VCH; Copyright 2024, Wang, H. et al.

Table 1 Representative quantitative metrics, ISC relevance, and limitations of 2D-material-enabled visual ISC platforms.

Platform	Representative example	Key metrics	ISC relevance	Limitation
TMD heterostructures	h-BN/WSe ₂ optical synapse [92]	405-655 nm; >90% recognition	Wavelength sensing; recognition	Contact resistance; uniformity
Defect-engineered 2D semiconductors	Bi ₂ Se ₃ optoelectronic synapse [93]	PPF: 201.7%; 523.1 s; 9.2 fJ spike ⁻¹	Temporal memory	Defect reproducibility
Anisotropic 2D materials	Black arsenic-phosphorus phototransistor [94]	2.88 A W ⁻¹ ; ratio: 4.7; 40 dB	Polarization vision	Air instability
2D perovskites	Monolithic 2D perovskite synapse [51]	~90 s; ~1.45 × 10 ⁻¹⁶ J event ⁻¹ ; 4 × accuracy	Image preprocessing	Ion drift; humidity sensitivity
2D framework materials	COF/MOF-based synaptic devices [95-97]	10 mV; ~1 fW; 10 ⁵ s; >90% classification	Low-power memory	Low mobility; film uniformity

Note: The reported performance metrics were obtained under different illumination wavelengths, optical powers, bias conditions, pulse parameters, and task settings. The listed values correspond to the specific experimental conditions reported in the original studies and provide a general comparison across different material platforms.

3 Photoinduced Synaptic Plasticity Mechanisms

The optoelectronic advantages of 2D materials can support visual ISC only when they are converted into controllable device responses. This conversion depends on photoinduced physical processes inside the channel, at the interface, or in the coupled

functional layers. These processes determine how optical inputs modulate conductance, how long the response can be retained, and whether the device can support repeatable synaptic behavior. Therefore, mechanism analysis is essential for connecting material properties with device functions. It also provides the basis for evaluating response speed, memory retention, stability, and application suitability in visual ISC systems.

3.1 Representative Photoinduced Synaptic Mechanisms

This section summarizes the main photoinduced mechanisms responsible for conductance modulation in 2D optoelectronic neuromorphic devices. These mechanisms include the photoconductive effect, trap-assisted photogating, persistent photoconductivity, interfacial charge transfer, ion migration, and ferroelectric polarization modulation. They may occur separately or coexist within one device. Their relative contributions are governed by the active material, interface quality, defect distribution, device architecture, and external bias. Understanding these mechanisms is important for evaluating plasticity, retention, and stability.

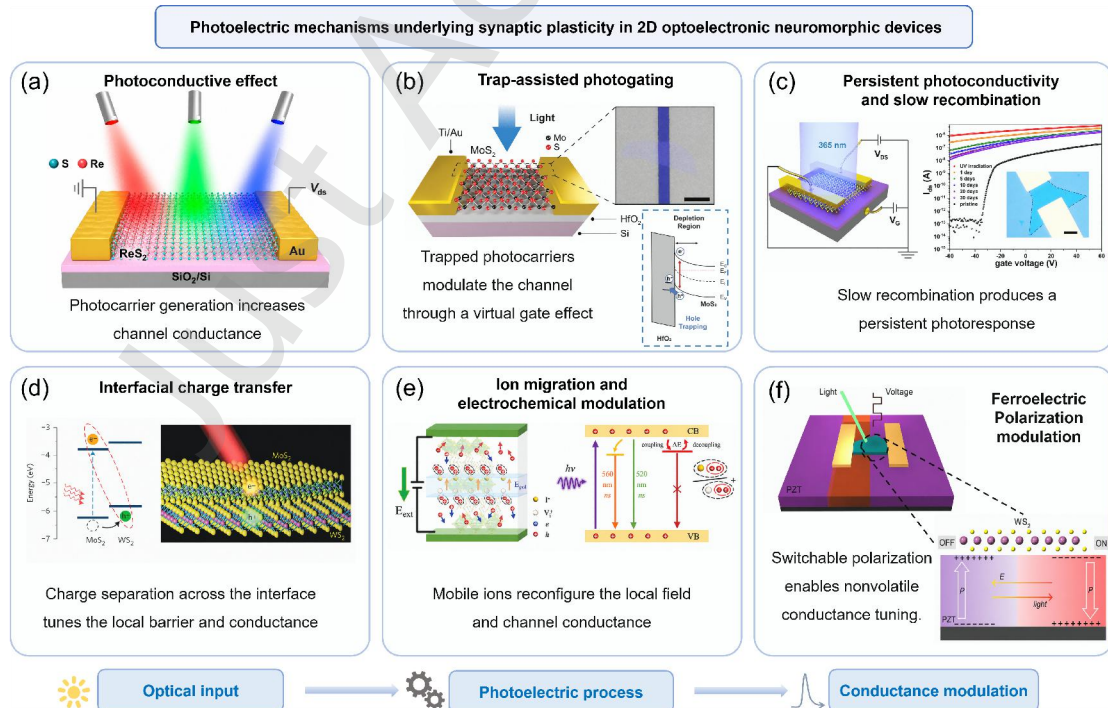
The photoconductive effect is the most direct photoresponse process. In Fig. 4(a), photon absorption generates electron-hole pairs in the 2D active material, increasing the free-carrier density and channel conductance under bias [98]. Because the excess carriers recombine after illumination, the photoconductive response is generally fast but provides limited memory. This mechanism is therefore more suitable for rapid optical sensing than for long-term synaptic storage. Trap-assisted photogating provides an effective route for light-induced synaptic plasticity. In the trap-mediated process illustrated in Fig. 4(b), part of the photogenerated carriers is captured by defects, dielectric layers, adsorbates, or interfacial states [99]. These trapped charges generate a local electric field and act as a virtual gate. The channel conductance can therefore remain modulated after the optical stimulus is removed. Shallow traps usually contribute to STP, while deeper traps can support LTP. Persistent

photoconductivity is closely related to this process. In Fig. 4(c), the persistent response originates from slow carrier recombination and long-lived trapped states [100]. It allows the device to retain part of the optical history and is useful for temporal integration, visual memory, and motion-related preprocessing. However, stronger retention often leads to slower recovery. A balance between memory and response speed is therefore required.

Interfacial charge transfer is important in 2D heterostructures. The mechanism summarized in Fig. 4(d) relies on band alignment and built-in electric fields at the junction [101]. These fields can drive photoinduced electrons and holes to different regions. The resulting charge separation changes the local barrier height and channel conductance. It can enhance photoresponse, regulate response polarity, and extend retention. Compared with single-material devices, heterostructures offer more design freedom. Band alignment, interface traps, and interlayer coupling can be engineered to regulate synaptic behavior. This mechanism is useful for wavelength-sensitive devices, heterojunction synaptic transistors, and light-programmable optoelectronic memristors. Ion migration and electrochemical modulation provide a slower but often stronger route for conductance regulation. Fig. 4(e) represents this ion-mediated process. In some 2D, quasi-2D, and hybrid materials, mobile ions or vacancies can redistribute under optical stimulation, electrical bias, or their combined action [51]. This redistribution changes the local electric field, carrier concentration, defect state, or interfacial barrier. It can produce large and sometimes nonvolatile conductance changes. These features are useful for multilevel synaptic weights and long-term memory. However, ion-related processes may also introduce hysteresis, drift, slow recovery, and endurance issues. These limitations become more critical in large arrays and repeated visual processing. Ferroelectric polarization modulation provides another route for nonvolatile synaptic control. In the ferroelectric/2D configuration in Fig. 4(f), a 2D channel is coupled with a ferroelectric layer [102]. Switchable polarization charges regulate the carrier density in the channel and enable reversible

conductance tuning. Optical stimulation may further interact with polarization-induced fields and interfacial charge trapping. This coupling can lead to optically assisted weight modulation and reconfigurable synaptic behavior. The performance of ferroelectric/2D hybrid devices depends strongly on polarization stability, interface quality, fatigue resistance, and the coupling strength between the ferroelectric layer and the 2D material.

These mechanisms provide different physical routes for photoinduced synaptic plasticity. The photoconductive effect favors fast carrier generation. Trap-assisted photogating and persistent photoconductivity provide memory and temporal integration. Interfacial charge transfer offers heterostructure-level control. Ion migration and ferroelectric polarization enable stronger and more nonvolatile modulation. In practical devices, multiple mechanisms often coexist. Identifying the dominant process is therefore important for rational device design and reliable visual ISC operation.



increased channel conductance in a ReS₂ optoelectronic synapse [98]. Copyright 2021, American Chemical Society. (b) Trap-assisted photogating through trapped photocarriers and virtual-gate modulation [99]. Copyright 2020, Nur, R. et al. (c) Persistent photoconductivity originating from slow carrier recombination and long-lived photoresponse [100]. Copyright 2021, George, A. et al. (d) Interfacial charge transfer in 2D heterostructures for local barrier and conductance modulation [101]. Copyright 2014, Springer Nature Limited. (e) Ion migration and electrochemical modulation for reconfigurable channel conductance [51]. Copyright 2024, Wang, Y. et al. (f) Ferroelectric/2D hybrid polarization modulation for nonvolatile conductance tuning [102]. Copyright 2020, American Chemical Society.

3.2 Mechanism comparison

The mechanisms discussed above differ in response speed, retention behavior, reversibility, stability, and suitability for visual ISC. Table 2 summarizes these differences. The qualitative descriptors used in the table represent general comparative trends rather than universal time-scale boundaries. Actual kinetic behavior depends largely on the material system, device structure, and operating conditions. The photoconductive effect usually provides the fastest response because it is mainly governed by photocarrier generation and transport. It is suitable for real-time optical sensing and fast visual signal acquisition. However, its memory capability is limited. In contrast, trap-assisted photogating and persistent photoconductivity provide stronger temporal retention. They are more useful for STP, LTP, temporal filtering, and memory-assisted visual preprocessing.

The balance between speed and memory is a central issue in mechanism selection. Fast carrier generation is useful for dynamic sensing, but it cannot retain optical history for long periods. Long-lived trapped carriers or slow recombination can improve memory retention, but they often slow down recovery and reset. This trade-off is important for visual ISC. Motion detection, event-like encoding, and temporal integration require a certain degree of memory. Real-time tracking and

high-speed image acquisition require faster response and recovery. Therefore, the best mechanism depends on the target visual task rather than on a single performance metric. Interfacial charge transfer, ion migration, and ferroelectric polarization provide more design freedom for long-term modulation. Interfacial charge transfer is attractive for heterostructure devices because band alignment and built-in fields can be engineered. It can support spectral selectivity, response polarity control, and tunable retention. Ion migration can generate large and multilevel conductance changes. It is useful for nonvolatile weight modulation, but it may introduce hysteresis, drift, and endurance problems. Ferroelectric modulation can provide more stable nonvolatile states, but its performance depends strongly on polarization stability and interface quality.

In practical 2D optoelectronic neuromorphic devices, these mechanisms rarely act in complete isolation. A heterostructure synapse may combine photoconductive response, interfacial charge transfer, and trap-assisted photogating. A perovskite or ion-containing system may couple carrier trapping with ion migration. A ferroelectric/2D hybrid device may involve both polarization modulation and interface trapping. Such coupling can enrich device functions, but it also increases the difficulty of mechanism identification and array control. Experimentally, the dominant mechanism can be identified by combining transient photoresponse, electrical characteristics, spectral dependence, and external-parameter-dependent measurements. Photoconductive responses generally follow optical excitation rapidly and recover after the light is removed, reflecting direct photocarrier generation and recombination. Photogating is more commonly associated with threshold-voltage shifts, persistent photocurrent, and slow relaxation caused by trapped photocarriers. Interfacial charge transfer can be examined through heterostructure-dependent spectral response and band-alignment analysis. Photoluminescence quenching and surface-potential measurements can provide additional evidence for interfacial carrier separation. Ion migration usually produces pronounced hysteresis, polarity dependence,

scan-rate-dependent electrical characteristics, and relatively slow relaxation. Temperature-dependent measurements can further reveal thermally activated ionic processes. These experimental signatures should be evaluated together because carrier trapping, interfacial transfer, and ionic motion may contribute simultaneously to the observed photoresponse. Therefore, mechanism comparison is not only a classification exercise. It provides guidance for selecting materials, designing device structures, and matching device dynamics with visual ISC functions.

In summary, photoinduced mechanisms should be evaluated according to the temporal and functional requirements of visual ISC. Fast photoconductive processes are suitable for rapid sensing. Trap-mediated and persistent responses provide temporal memory. Interfacial charge transfer enables tunable spectral and heterostructure functions. Ionic and ferroelectric processes support stronger or more persistent conductance modulation. Mechanism selection should therefore consider response speed, retention, reversibility, stability, and the target visual task together.

Table 2. Comparison of photoinduced synaptic plasticity mechanisms in 2D optoelectronic neuromorphic devices.

Mechanism	Main process	Response speed	Retention	Suitable ISC function	Main limitation
Photoconductive effect [99]	Photocarrier generation	Fast	Short	Fast sensing	Weak memory
Trap-assisted photogating [103]	Virtual-gate trapping	Medium	Short to long	Temporal plasticity	Drift and trap variation
Persistent photoconductivity [70]	Slow recombination	Slow to medium	Long	Visual memory	Slow recovery
Interfacial charge transfer [101]	Interfacial charge separation	Medium	Tunable	Spectral sensing	Interface reproducibility
Ion migration [51]	Ion/vacancy migration	Slow	Long/nonvolatile	Multilevel memory	Hysteresis and endurance issues
Ferroelectric modulation [102]	Polarization gating	Medium	Long/nonvolatile	Nonvolatile memory	Fatigue and interface quality

Note: Terms such as “fast,” “medium,” “slow,” “short,” and “long” are used to indicate general qualitative trends. Actual response times and retention times depend

on the material system, device architecture, illumination conditions, applied bias, and measurement protocol.

4 Device Architectures and Synaptic Plasticity

Device architecture determines how material properties and photoinduced mechanisms are translated into neuromorphic functions. In 2D optoelectronic devices, the same material system can exhibit different synaptic behaviors when it is configured as a phototransistor, photomemristor, floating-gate device, ion-gated transistor, or vertical synapse. The device structure affects carrier injection, charge trapping, interfacial coupling, ionic modulation, and electrical readout [104]. It also determines optical sensitivity, conductance tunability, memory retention, response speed, and array compatibility. For visual ISC, device architecture must support not only light sensing, but also state modulation, stable readout, and multidimensional optical input. Therefore, architecture design provides the bridge between photoinduced mechanisms and visual ISC functions. To organize the diverse device implementations, this section uses the dominant structural or modulation feature as the primary descriptor. These descriptors belong to different classification dimensions and can coexist within the same device. Device geometry includes lateral and vertical transport configurations. Modulation strategies include field-effect, floating-gate, ion-gated, and memristive operation. Heterojunction and mixed-dimensional designs describe the interface configuration. Polarization sensitivity represents a functional specialization. Representative devices are discussed according to the feature that most directly determines their neuromorphic operation and relevance to visual ISC.

4.1 Representative device configurations

2D optoelectronic synaptic devices have been developed into several representative architectures. These architectures differ in how optical signals are coupled into the active channel and how the resulting conductance states are stored or read out. Field-effect devices mainly use light-induced carrier modulation in a 2D

channel. Trap-layer, floating-gate, and heterointerface-based devices prolong the optical response through charge storage or interfacial coupling. Other architectures use polarization sensitivity, ionic modulation, memristive switching, or vertical transport to expand the operating mode. These structural differences lead to different balances among optical sensitivity, memory retention, programmability, and integration density. Fig. 5 includes both demonstrated optoelectronic synaptic devices and related 2D device architectures that serve as structural references for future neuromorphic vision hardware

Field-effect and gate-modulated architectures provide the most common platform for 2D optoelectronic synapses. In a phototransistor synapse, optical stimulation changes the channel carrier density and modulates the drain current, enabling light-gated conductance regulation, as illustrated in Fig. 5(a). This structure is useful for sensitive optical sensing and electrical readout [105]. A trap-layer-assisted phototransistor introduces an additional trapping interface or dielectric layer, as shown in Fig. 5(b). Photogenerated carriers can be trapped and released at this layer, producing trap-assisted photogating and tunable synaptic responses [106]. A floating-gate optoelectronic synapse further uses a charge storage layer to retain optical or electrical programming history, as represented in Fig. 5(c) [107]. This architecture is suitable for nonvolatile conductance modulation, but it requires careful control of tunneling, leakage, and charge retention.

Functional and memristive architectures expand the information dimensions and storage modes of 2D optoelectronic synapses. A polarization-sensitive phototransistor synapse uses anisotropic 2D materials or polarization-dependent heterostructures to regulate channel conductance according to the polarization state of incident light, as shown in Fig. 5(d). This architecture is suitable for polarization vision and orientation-sensitive perception [108]. A two-terminal photomemristor provides a more compact device geometry, as shown in Fig. 5(e). Optical inputs can regulate the resistive or conductance state, allowing optical weight storage in a simple structure

[109]. This design is attractive for high-density arrays, although switching variability and readout disturbance remain important issues. A multi-terminal optoelectronic synaptic transistor separates optical input, electrical programming, and output readout, as illustrated in Fig. 5(f) [110]. This structure provides higher control flexibility and allows programmable plasticity through coupled optical and electrical inputs.

Ion-gated, heterojunction, and vertical architectures provide additional routes for conductance modulation and compact integration. The ion-gated synaptic transistor in Fig. 5(g) uses electrolyte-mediated ionic motion to regulate the carrier density in a 2D channel [111]. This structure can produce large conductance modulation at low operating voltage, although the reported synaptic response is mainly controlled by electrical gating. The mixed-dimensional van der Waals phototransistor in Fig. 5(h) employs a Te/ReS₂ heterojunction to regulate light-sensitive carrier transport through interfacial band alignment and charge separation [112]. Its band alignment and interfacial carrier separation provide a route for enhancing light-sensitive channel modulation. Although this device was not demonstrated as an ion-gated synapse, the heterojunction design is relevant to future optoelectronic synaptic devices. The electrolyte-gated vertical synapse array in Fig. 5(i) uses stacked van der Waals layers and out-of-plane transport to reduce the lateral device footprint [113]. Its synaptic modulation is mainly electrical, but the compact vertical configuration provides a useful structural reference for high-density optoelectronic neuromorphic integration. Overall, different architectures offer different trade-offs. Phototransistors favor sensitive sensing. Floating-gate and memristive devices favor memory storage. Polarization-sensitive structures provide multidimensional encoding. Ion-gated devices support strong conductance tuning, while vertical devices improve integration density. The choice of architecture should therefore match the target ISC task and the required balance among speed, memory, stability, and scalability.

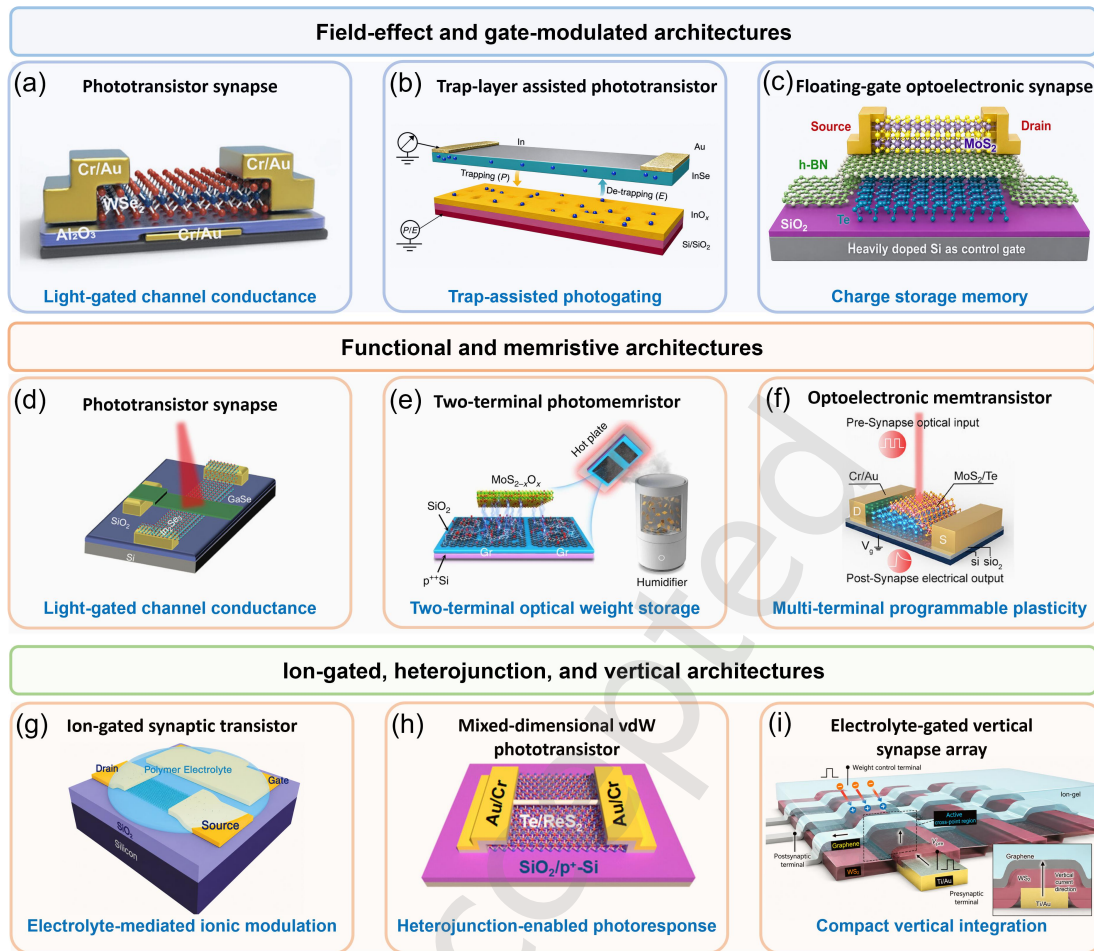


Figure 5 Representative 2D optoelectronic synaptic device architectures for visual ISC. (a) Phototransistor synapse based on light-gated channel conductance modulation [105]. Copyright 2023 Wiley - VCH. (b) Trap-layer-assisted phototransistor [106]. Copyright 2020, Yang, F. S. et al. (c) Floating-gate optoelectronic synapse with charge-storage memory [107]. Copyright 2023 Wiley - VCH. (d) Polarization-sensitive phototransistor synapse [108]. Copyright 2021 Wiley - VCH. (e) A two-terminal photomemristor for optical weight storage [109]. Copyright 2022, Fu, X. et al. (f) Optoelectronic synaptic transistor with multi-terminal operation [110]. Copyright 2025, Wiley - VCH. (g) Ion-gated synaptic transistor based on electrolyte-mediated ionic modulation [111]. Copyright 2018, Wiley - VCH. (h) Mixed-dimensional van der Waals phototransistor based on interfacial carrier modulation [112]. Copyright 2021, American Chemical Society. (i) Electrolyte-gated vertical synapse array with compact out-of-plane transport [113]. Copyright 2021, Seyong, O. et al.

4.2 Light-regulated synaptic plasticity

Light-regulated synaptic plasticity describes how optical stimuli modulate the conductance state of 2D optoelectronic neuromorphic devices. This process provides the functional basis for visual sensing, memory, and front-end computing. A single optical pulse can induce an EPSC, as represented in Fig. 6(a). The amplitude and decay profile of EPSC reflect the optical sensitivity, carrier relaxation, and short-term memory of the device [114]. When two optical pulses are applied with a short interval, the second response can be enhanced due to residual carriers, trapped charges, or incompletely recovered ionic states. This paired-pulse facilitation (PPF) behavior, shown in Fig. 6(b), is commonly used to evaluate short-term temporal correlation and synaptic facilitation [115].

The transition from STP to LTP is another important feature of light-regulated synapses. Weak or brief optical stimulation usually produces a transient conductance change. Stronger, longer, or repeated stimulation can drive the device into a more persistent state, as shown in Fig. 6(c) [116]. This STP-LTP transition allows optical history to be stored in the conductance state. Pulse-width-dependent plasticity further shows that longer illumination can produce stronger or more persistent responses, as summarized in Fig. 6(d) [117]. Pulse-number-dependent potentiation, shown in Fig. 6(e), indicates that repeated optical pulses can gradually modulate conductance and form memory states [118]. These behaviors are important for temporal accumulation, adaptive sensing, and memory-assisted visual preprocessing.

Optical pulses can also encode information through frequency, wavelength, and polarization. Frequency-dependent responses arise when the device cannot fully relax between adjacent pulses. As a result, residual photoinduced states accumulate and produce stronger conductance modulation, as illustrated in Fig. 6(f) [119]. Wavelength-dependent responses, shown in Fig. 6(g), originate from differences in absorption, band alignment, defect states, or interfacial charge transfer under different

photon energies [120]. This property enables spectral selectivity and wavelength-resolved visual encoding. Polarization-sensitive responses, represented in Fig. 6(h), are mainly observed in anisotropic 2D materials or polarization-sensitive heterostructures [121]. They allow optical polarization or orientation information to be converted into electrical signals, which is useful for multidimensional visual perception. Multilevel conductance modulation is essential for analog weight storage and visual ISC. In Fig. 6(i), multiple effective conductance states can be generated under controlled pulse conditions [92]. These states can represent synaptic weights, optical memory levels, or encoded visual features. However, a large number of conductance states alone is not sufficient. Linearity, symmetry, retention, noise, cycle-to-cycle variation, and device-to-device uniformity are also important for reliable computing. Overall, Fig. 6 shows that optical input is not a single stimulus variable. Light intensity, pulse width, pulse number, frequency, wavelength, and polarization can all serve as programmable dimensions for regulating synaptic plasticity in 2D optoelectronic neuromorphic devices.

In summary, device architecture determines how material-level photoresponses are converted into usable neuromorphic functions. Phototransistor configurations favor sensitive optical sensing and flexible electrical control. Floating-gate and memristive structures provide stronger memory capability. Ion-gated devices enable large conductance modulation at low voltage. Vertical configurations are attractive for high-density integration. The appropriate architecture should be selected according to the required sensing mode, memory dynamics, control flexibility, and array scalability.

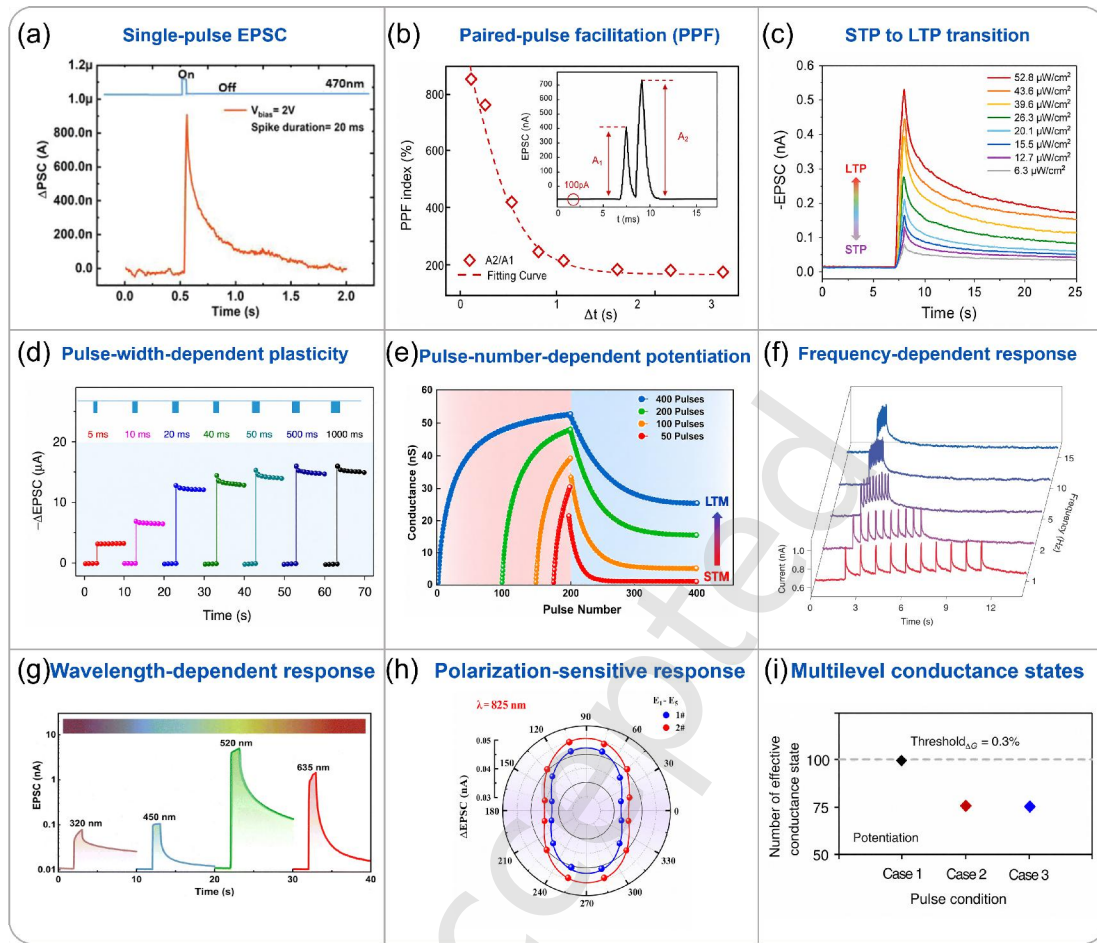


Figure 6 Light-regulated synaptic plasticity and multidimensional modulation in 2D optoelectronic neuromorphic devices. (a) Single-pulse EPSC response [114]. Copyright 2019, Wiley - VCH. (b) Paired-pulse facilitation [115]. Copyright 2023, Liu, X. X. et al. (c) STP-LTP transition regulated by optical stimulation [116]. Copyright 2024, Wiley - VCH. (d) Pulse-width-dependent plasticity [117]. Copyright 2022, Zhu, C. et al. (e) Pulse-number-dependent potentiation and memory evolution [118]. Copyright 2021, Wiley - VCH. (f) Frequency-dependent synaptic response [119]. Copyright 2022, Springer Nature. (g) Wavelength-dependent optical response [120]. Copyright 2024, Royal Society of Chemistry. (h) Polarization-sensitive synaptic response [121]. Copyright 2025, American Chemical Society. (i) Multilevel conductance modulation for synaptic weight storage [92]. Copyright 2018, Seo, S. et al.

5 Array Integration and Front-End Computing

Single 2D optoelectronic synaptic devices are useful for revealing photoinduced plasticity, memory behavior, and light-regulated conductance modulation. However, visual ISC requires more than isolated device responses. Visual information is spatially distributed and time dependent. It must be sensed, stored, addressed, and processed across many pixels. Therefore, array integration is a key step in moving 2D optoelectronic neuromorphic devices from single-device demonstrations toward visual hardware systems. In this context, array design should provide reliable pixel addressing, parallel optical input, stable readout, and compatibility with front-end computing circuits.

5.1 From single devices to addressable arrays

The first requirement for visual ISC is to integrate individual optoelectronic synapses into addressable pixel arrays. In an addressable array, each pixel should respond to local optical stimulation and maintain its own conductance or photoresponse state. Row and column selection allows the state of each pixel to be programmed or read without measuring every device separately [122-124]. The addressable optoelectronic synapse pixel array in Fig. 7(a) represents this basic transition from single devices to spatially organized visual hardware [125]. Such arrays can convert optical images into current or conductance maps, which provide the physical basis for image sensing and early preprocessing.

Passive crossbar arrays provide a compact route for high-density integration. In the crossbar-like structure shown in Fig. 7(b), 2D optoelectronic synaptic units are located at the intersections of top and bottom electrodes [62]. This geometry is attractive for parallel optical input, analog current summation, and matrix-based operations. It also matches the requirements of dense neuromorphic arrays. However, passive crossbars may suffer from sneak current, crosstalk, and readout disturbance. These issues become more serious as the array size increases. Device uniformity and

selector design are therefore important for reliable crossbar operation.

Active-matrix pixel arrays provide another addressing strategy. The active-matrix photodetector array in Fig. 7(c) uses gate and data lines to select pixels more precisely. This architecture can suppress crosstalk and improve readout reliability [126]. It is closer to mature imaging circuits and is suitable for large-area visual sensing. The trade-off is higher circuit complexity and larger pixel footprint. For 2D optoelectronic visual ISC, the choice between passive crossbar and active-matrix addressing depends on the target task. Dense analog computation may favor crossbar structures. High-fidelity imaging and stable pixel selection may require active-matrix designs.

5.2 Array-level readout and computing

After array integration, the next challenge is to convert distributed pixel responses into useful visual information. Optical programming and in-sensor preprocessing provide one route, as illustrated in Fig. 7(d). Optical images can directly program local conductance states across the array [127]. The stored response pattern can then be used for image preprocessing, feature extraction, or sensory classification. This mode reduces the need to transfer all raw optical data to external processors. It also allows part of the visual information to be filtered or compressed at the sensor front end.

Matrix readout is important for linking device arrays with computing functions. In the conductance or photoresponsivity matrix shown in Fig. 7(e), each pixel or subpixel contributes a weighted response [128]. The output current reflects the combined effect of optical input and local device state. This enables weighted accumulation, spatial mapping, and analog feature extraction. Such matrix-based readout is useful for visual ISC because it allows sensing and computation to share the same physical substrate. However, the accuracy of this process depends on device uniformity, conductance linearity, readout noise, and stability of the programmed states.

Peripheral circuits are required to interface 2D optoelectronic arrays with system-level computation. The circuit interface in Fig. 7(f) shows how array readout can be combined with complementary metal oxide semiconductor (CMOS) circuits and matrix-vector multiplication (MVM) [129]. In practical systems, peripheral circuits provide biasing, pixel selection, signal integration, analog-to-digital conversion, and communication with downstream processors. This interface is essential because most 2D optoelectronic arrays still require external control and readout electronics. The performance of visual ISC systems therefore depends not only on the active material and device array, but also on the co-design of sensing pixels, readout circuits, and computing algorithms.

As visual ISC evolve from single-device to array-level and system-level operations, the location of each processing step becomes increasingly important. At the device or array level, optical sensing can be directly combined with local storage, time integration, filtering, feature encoding, and weighted signal summation[127, 128, 130, 131]. These operations allow some visual information to be processed before it leaves the sensor. Peripheral electronics are typically introduced to provide pixel addressing, bias control, signal conditioning, and array readout functions [129]. These components form the interface between the sensing array and downstream computing modules. Consequently, in many current demonstrations, the hardware is responsible for sensing and early feature processing, while classification or decision-making is performed by an external processor or offline algorithms. Systems with higher levels of integration may further incorporate circuit-level computation, extending processing capabilities beyond front-end feature extraction. This distinction is important when evaluating the actual degree of ISC achieved by different hardware platforms.

5.3 Key metrics for array integration

Front-end computing extends array function beyond image acquisition. The programmable photodiode network in Fig. 7(g) demonstrates in-array convolution or

filtering [130]. Such networks can implement basic image processing operations before data leave the sensor. This is important for edge detection, denoising, contrast enhancement, and feature selection. Parallel accumulation and current-to-feature mapping, represented in Fig. 7(h), further show how array currents can be transformed into feature maps [131]. These operations reduce data redundancy and provide more compact inputs for recognition or decision-making.

Array-level benchmarking is necessary for evaluating whether a 2D optoelectronic system can move toward practical visual ISC. The metrics summarized in Fig. 7(i) include yield, scalability, uniformity, linearity, number of conductance states, processing temperature, and transfer compatibility [132]. These metrics are more relevant to system performance than single-device plasticity alone. A device with excellent excitatory postsynaptic current or long retention may still fail in arrays if pixel variation is large or readout noise is high. Similarly, a high number of conductance states is useful only when these states are stable, reproducible, and distinguishable across many pixels.

Several nonideal factors remain critical. Material thickness variation, grain boundaries, transfer residues, contact resistance, and interface traps can produce fixed-pattern noise and pixel-to-pixel variation. Crosstalk and sneak current may distort the readout in dense arrays. Thermal budget and transfer compatibility also determine whether 2D devices can be integrated with existing electronic platforms. Therefore, future array-level studies should report not only synaptic behaviors, but also statistical device variation, yield, array size, energy consumption, retention distribution, and recognition performance under realistic conditions. Reliable visual ISC will require coordinated optimization of material growth, device architecture, addressing scheme, readout circuit, and task-specific algorithm.

In summary, array integration represents the transition from device-level plasticity to functional visual hardware. Practical visual ISC requires addressable

pixels, uniform device responses, stable conductance states, low-noise readout, and compatible peripheral circuits. Array performance should therefore be evaluated through system-relevant metrics such as yield, variability, scalability, energy consumption, readout fidelity, and task-level performance.

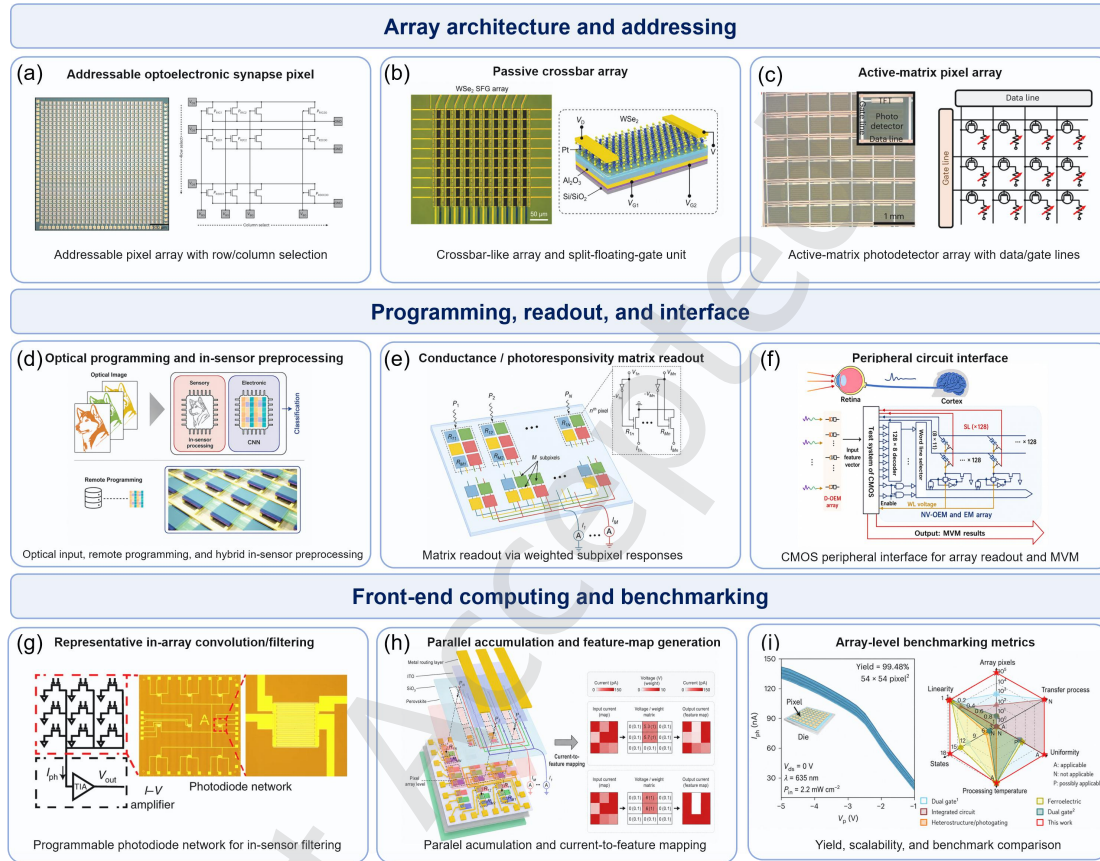


Figure 7 Array integration, addressing, and front-end computing in 2D optoelectronic neuromorphic systems. (a) Addressable optoelectronic synapse pixel array with row and column selection [125]. Copyright 2022, Springer Nature. (b) Passive crossbar array for parallel optical input and synaptic modulation [62]. Copyright 2024, Peng, Z., et al. (c) Active-matrix pixel array with gate and data-line addressing [126]. Copyright 2025, Springer Nature. (d) Optical programming and in-sensor preprocessing for sensory classification [127]. Copyright Lee, S. et al. 2022. (e) Conductance or photoresponsivity matrix readout through weighted subpixel responses [128]. Copyright 2020, Springer Nature. (f) CMOS peripheral interface for array readout and matrix-vector multiplication [129]. Copyright 2024, Springer Nature. (g) Programmable photodiode network for in-array convolution and filtering [130].

Copyright 2022, Springer Nature. (h) Parallel accumulation and current-to-feature mapping for feature-map generation [131]. Copyright 2024, Zhang, T. et al. (i) Array-level benchmarking metrics, including yield, scalability, uniformity, linearity, conductance-state number, processing temperature, and transfer compatibility [132]. Copyright 2026, Springer Nature.

6 Visual ISC Functions and System Maturity

Visual ISC is a key application direction of 2D optoelectronic neuromorphic devices. It aims to perform part of the visual information processing at the sensor front end. The hardware contribution can range from device-level sensing and memory to array-level encoding, filtering, and feature extraction. Peripheral circuits may provide addressing, readout, and signal conversion. Final classification or decision-making may still rely on external processors or offline algorithms in many current demonstrations. Current demonstrations show different levels of maturity. Some studies focus on single-device synaptic response, while others have moved toward pixel arrays, front-end preprocessing, and system-level visual tasks. Therefore, it is necessary to distinguish proof-of-concept demonstrations from array-level and system-level ISC.

6.1 Multidimensional maturity framework of visual ISC

Fig. 8 presents a multidimensional framework for evaluating the development of visual ISC from three complementary perspectives: hardware scale, computing capability, and validation level. These dimensions describe different aspects of system development and should not be interpreted as a fixed linear sequence. Progress along one dimension does not necessarily imply equivalent progress along the others. For example, a large-scale pixel array may provide parallel sensing with limited in-sensor computation, whereas a smaller prototype may demonstrate more advanced temporal processing or task-specific functions. The three dimensions are therefore evaluated separately and together provide a more complete description of system maturity. At

the hardware scale, current studies have progressed from single-device validation to pixel-array integration and system-level implementation [133]. In the proof-of-concept stage, a single optoelectronic device is used to verify light-induced conductance modulation, as represented in Fig. 8(a) [29]. This level is important for confirming photoresponse and basic synaptic behavior, but it does not yet demonstrate spatial visual processing. Pixel-array integration further enables parallel sensing and spatial mapping, as illustrated in Fig. 8(b) [134]. At this stage, optical images can be converted into conductance or current maps. More advanced systems combine optoelectronic memory arrays with peripheral controllers and circuit modules, as shown in Fig. 8(c) [135]. This integration is required for closed-loop visual sensing, readout, and task-level operation.

The second dimension is computing capability. Basic demonstrations usually focus on photoresponse, signal accumulation, and memory decay. These behaviors, summarized in Fig. 8(d), indicate whether the device can retain optical history and support simple synaptic functions [136]. Array-level ISC moves beyond device response by performing in-sensor preprocessing. As shown in Fig. 8(e), optical inputs can be compressed, encoded, or transformed into useful features before back-end computation [137]. This reduces redundant data transfer and shifts part of the visual workload to the sensor front end. At a higher computing level, ISC systems should support inference and decision-making. The example in Fig. 8(f) shows how event spikes, output neurons, and classification units can convert sensory signals into task-level decisions [17]. This stage requires coordinated operation among devices, arrays, circuits, and algorithms.

The third dimension is validation level. Laboratory-level demonstrations, such as the in-pixel encoding and offline classification shown in Fig 8(g), are useful for proving feasibility under controlled conditions. In this case, optical encoding is implemented at the pixel level, while classification is completed by an offline algorithm. Such demonstrations therefore represent partial hardware implementation

of the visual processing pipeline. However, they often rely on external processing and simplified inputs. Task-level demonstrations move closer to practical visual functions. For example, the motion perception and direction recognition in Fig. 8(h) require temporal information, spatial feature extraction, and task-oriented decoding [138]. Real-time vision prototypes represent a more demanding stage. In Fig. 8(i), event frames, memory frames, and analog processing are used to handle continuous visual input [139]. Such systems are closer to real visual ISC because they require fast response, memory-assisted processing, and stable operation over time. However, this hierarchy also shows that visual ISC cannot be evaluated only by single-device synaptic behavior [140]. A device with clear light-induced plasticity may still be far from practical visual computing if it lacks array integration, reliable readout, or task-level validation. To provide a more explicit comparison, Table 3 summarizes the maturity levels of visual ISC from material response to real-time system prototypes. The evaluation metrics include device response, synaptic memory, array uniformity, task accuracy, latency, power consumption, and real-scene robustness. These metrics represent key parameters for assessing different levels of visual ISC development. Their values depend on the device platform, array configuration, operating conditions, and target task. Overall, the three dimensions provide complementary criteria for assessing visual ISC systems. Their development can proceed at different rates depending on the device platform and target application. Practical visual ISC requires an appropriate combination of hardware integration, computing capability, and task-level validation. This multidimensional framework provides a more flexible basis for comparing systems with different development paths and technological objectives.

Table 3. Maturity levels and evaluation metrics of visual ISC based on 2D optoelectronic neuromorphic devices

Level	Hardware scale	Evaluation metrics	Main limitation
Material response [141]	Single material/device	Responsivity; detectivity; response time	Material instability
Device plasticity [93]	Single device	EPSC; PPF index; STP/LTP ratio	Drift and hysteresis

Synaptic memory [51]	Single device/pixel	Retention time; endurance; energy/spike	Speed-retention trade-off
Multilevel modulation [132]	Single device/pixel	Conductance states; linearity; nonlinearity factor	State overlap
Pixel encoding [92]	Single pixel	Dynamic range; noise level; encoding accuracy	Limited spatial mapping
Small-array mapping [75]	Pixel array	Array size; pixel yield; uniformity	Pixel variation
Array preprocessing [137]	Addressable array	SNR; data reduction ratio; accuracy gain	Crosstalk; readout noise
Task-level ISC [138]	Array + algorithm	Recognition accuracy; latency; robustness	Hardware-algorithm mismatch
Circuit-assisted ISC [77]	Array + peripheral circuit	MVM accuracy; ADC cost; bandwidth	Peripheral overhead
Real-time prototype [16]	Integrated system	Total power; end-to-end latency; real-scene accuracy	System reliability

Note: The listed levels represent reference points for comparing visual ISC development and do not imply a fixed linear progression. Hardware scale, computing capability, and validation level may evolve independently across different device platforms and applications.

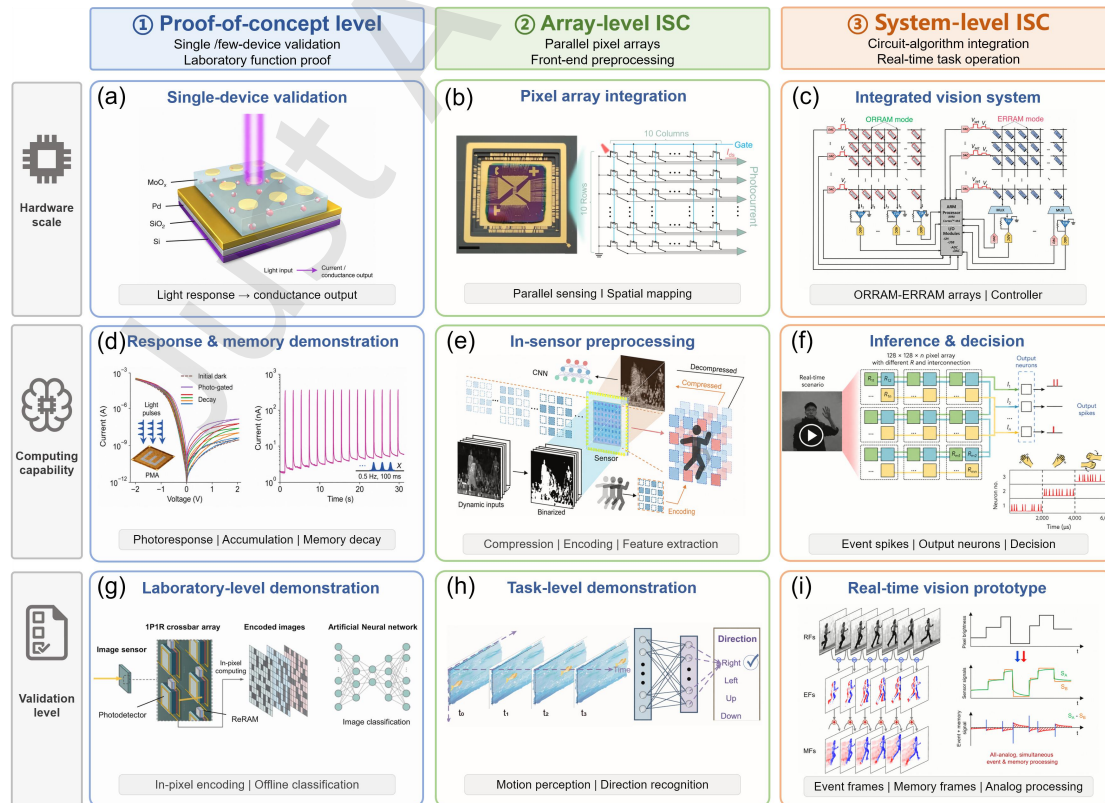


Figure 8 Multidimensional maturity framework of visual ISC based on optoelectronic neuromorphic devices. (a) Single-device validation, light-induced conductance modulation [29]. Copyright 2019, Springer Nature. (b) Pixel-array integration, parallel optical sensing and spatial mapping [134]. Copyright 2023, Huang, P. Y. et al. (c) Integrated vision system, optoelectronic memory arrays with peripheral control circuits [135]. Copyright 2023, Zhou, G. et al. (d) Response and memory, photoresponse, accumulation, and memory decay [136]. Copyright 2023, Tan, H., van Dijken, S. (e) In-sensor preprocessing, compression, encoding, and feature extraction [137]. Copyright 2025, Huang, H. et al. (f) Inference and decision, event spikes, output neurons, and task-level classification [17]. Copyright 2023, Springer Nature. (g) Laboratory-level demonstration, in-pixel encoding and offline classification [73]. Copyright 2022, Lee, D. et al. (h) Task-level demonstration, motion perception and direction recognition [138]. Copyright 2025, Yang, Y. et al. (i) Real-time vision prototype, event-frame generation, memory-frame processing, and analog optoelectronic computation [139]. Copyright 2025, Kim, Y. et al.

6.2 Representative visual ISC functions

Representative visual ISC functions can be divided into static image preprocessing, dynamic visual processing, and multidimensional visual perception. These functions reflect different levels of front-end information processing. Static preprocessing mainly improves image quality and extracts basic spatial features before back-end recognition [142]. Dynamic processing focuses on temporal changes, motion cues, and event-like responses [143]. Multidimensional perception further extends visual encoding from intensity-based sensing to spectral, spatial, polarization, and noise-robust information processing [144]. As summarized in Fig. 9, these functions show how optoelectronic neuromorphic devices can reduce redundant visual data and provide more useful features for downstream computation.

Static image preprocessing is one of the most direct visual ISC functions. Image denoising suppresses noise at the sensor front end before the signal enters a

recognition network, as represented in Fig. 9(a) [145]. This operation can improve the quality of visual inputs and reduce the burden on digital post-processing. Contrast enhancement converts weak or low-contrast optical inputs into clearer electrical or visual outputs, as shown in Fig. 9(b) [146]. This function is useful for dim-light imaging, weak target detection, and adaptive vision. Edge detection extracts boundaries and structural information from images, as illustrated in Fig. 9(c) [147]. Since edges contain important spatial features, in-sensor edge extraction can reduce data volume while preserving key information for object localization and pattern recognition.

Dynamic visual processing requires the sensor to respond to temporal changes rather than static intensity alone. Motion detection identifies moving regions by comparing changes between frames or by using the time-dependent response of the device, as shown in Fig. 9(d) [148]. Trajectory tracking further records the position and movement path of an object over time, as represented in Fig. 9(e) [149]. These functions require short-term memory and temporal correlation, because the device must compare current optical inputs with previous states. Event-like dynamic encoding provides a more efficient route for processing dynamic scenes. In Fig. 9(f), asynchronous and sparse responses are generated when visual changes occur [150]. This mode avoids continuous frame acquisition and is useful for low-power, high-speed, and motion-sensitive vision.

Multidimensional visual perception uses additional optical dimensions to enrich visual representation. Spectral-spatial feature fusion combines wavelength-dependent response with spatial imaging, as shown in Fig. 9(g) [116]. This allows the system to extract features that cannot be obtained from intensity images alone. Polarization-sensitive vision uses polarization-dependent photoresponse to enhance contrast and distinguish orientation-related information, as illustrated in Fig. 9(h) [151]. This function is useful for reflective surfaces, low-contrast objects, and hidden feature detection. Noise-robust pattern recognition, represented in Fig. 9(i), shows

how preprocessed optical or electrical outputs can improve recognition accuracy under noisy inputs [152]. Overall, these examples show that visual ISC can extend beyond image acquisition to front-end denoising, enhancement, feature extraction, motion analysis, and multidimensional encoding. These hardware-generated features can then be used for downstream recognition or decision-making. In some integrated systems, part of the inference process can also be implemented with peripheral computing hardware. The required device properties differ across tasks. Static preprocessing benefits from nonlinear response and low noise. Dynamic processing requires controlled relaxation and temporal memory. Multidimensional perception relies on wavelength or polarization selectivity.

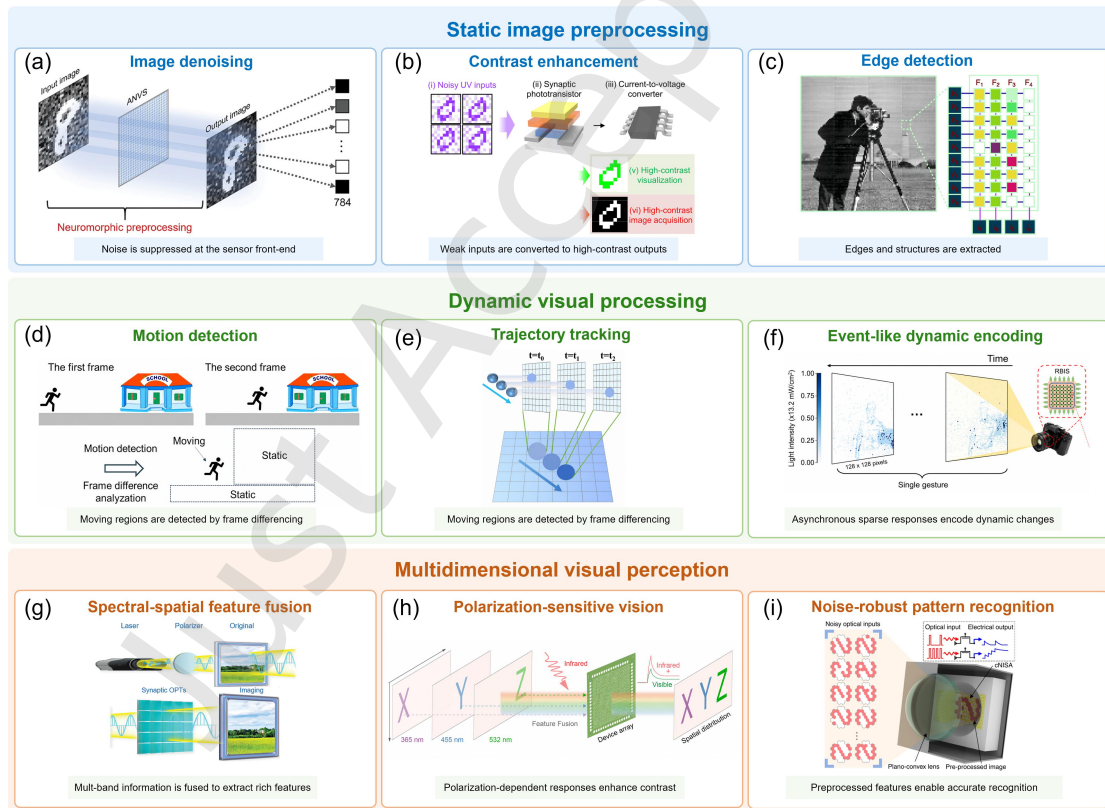


Figure 9 Representative visual ISC functions based on optoelectronic neuromorphic devices.

(a) Image denoising at the sensor front end [145]. Copyright 2024, Wiley - VCH. (b) Contrast enhancement of weak optical inputs [146]. Copyright 2022, The American Association for the Advancement of Science. (c) Edge detection for structural feature extraction [147]. Copyright 2020, Wiley - VCH. (d) Motion detection by frame-difference

analysis [148]. Copyright 2024, American Chemical Society. (e) Trajectory tracking of moving objects [149]. (f) Event-like dynamic encoding of temporal changes [150]. Copyright 2025, Gao, H. et al. (g) Spectral-spatial feature fusion for enriched visual representation [116]. Copyright 2024, Wiley - VCH. (h) Polarization-sensitive vision for contrast enhancement and feature discrimination [151]. Copyright 2026, Wiley - VCH (i) Noise-robust pattern/object recognition through in-sensor preprocessing [152]. Copyright 2020, Choi, C. et al.

7 Challenges and Outlook

Although 2D optoelectronic neuromorphic devices have shown great potential for visual ISC, most current demonstrations remain far from deployable systems. The main challenge is no longer only to obtain light-induced synaptic behavior in a single device. Practical visual ISC requires stable materials, reproducible devices, addressable arrays, reliable readout circuits, and task-oriented algorithms [153, 154]. These requirements are closely coupled. A material with strong photoresponse may still fail in large arrays if film uniformity is poor [155, 156]. A device with long retention may be unsuitable for dynamic vision if recovery is too slow. An array with good sensing performance may still be limited by crosstalk, calibration cost, or peripheral circuit complexity. Therefore, deployable 2D optoelectronic visual ISC should be considered as a cross-scale problem from materials to systems.

7.1 Challenges from materials to systems

Material nonuniformity and instability remain major barriers to deployable 2D optoelectronic visual ISC. For many 2D and quasi-2D materials, variations in thickness, grain size, defect density, and surface contamination can lead to large pixel-to-pixel differences [157]. Environmental effects, including oxidation, moisture sensitivity, ion migration, and interface degradation, further reduce long-term reliability [158]. These issues are especially critical for large-area visual arrays, where small material fluctuations can appear as fixed-pattern noise or response mismatch

[159]. As illustrated in Fig. 10(a), wafer-scale growth, controlled transfer, interface passivation, and defect regulation are needed to improve film uniformity, yield, and operational stability [160, 161]. Future studies should report not only single-device performance, but also spatial statistics across wafers or arrays.

Device reliability is mainly limited by drift, hysteresis, and the speed-retention trade-off. Many optoelectronic synapses rely on carrier trapping, ion migration, or persistent photoconductivity to obtain memory [162]. These processes can improve retention, but they may also slow recovery and cause instability during repeated operation. Dynamic visual tasks require a device to respond quickly to new optical inputs while retaining useful temporal information [163]. This balance is difficult to achieve. Fig. 10(b) highlights interface engineering and trap control as key strategies [164]. Stable dielectric interfaces, optimized trap distributions, and controlled ionic pathways can reduce unwanted drift and improve endurance. Important device metrics include retention, endurance, response time, recovery time, and energy per event. Array integration introduces additional problems, including crosstalk, sneak current, readout noise, and device variation [165]. A single device may show clear synaptic plasticity, but array operation requires many devices to behave consistently. Passive crossbar arrays can provide high density, but they are vulnerable to leakage paths and readout disturbance [166]. Active-matrix arrays can improve addressability, although they increase circuit complexity and pixel area. As shown in Fig. 10(c), active-matrix designs, selector elements, calibration, and compensation strategies are needed for reliable array operation [133]. Array-level evaluation should include signal-to-noise ratio, pixel uniformity, array size, yield, retention distribution, and variation after repeated optical or electrical programming.

System deployment is restricted by the mismatch between device characteristics and real visual tasks. Many reported demonstrations still use simplified images, offline classification, or controlled illumination [167-169]. Real scenes contain motion, changing brightness, background noise, occlusion, and complex temporal

information. A visual ISC system must therefore combine device-level sensing and memory with circuit-level readout and algorithm-level adaptation. Fig. 10(d) emphasizes hardware-algorithm co-design and closed-loop calibration. Device dynamics should be matched with the target task [170]. Fast photoconductive devices are suitable for real-time sensing, while trap- or ion-mediated devices are more suitable for temporal integration or memory-assisted preprocessing. System-level metrics should include latency, power, recognition accuracy, robustness under noise, and performance in real-world scenes.

7.2 Future directions and quantitative benchmarks

Future progress in 2D optoelectronic visual ISC should move from isolated performance optimization toward cross-scale co-design. Advanced materials remain the starting point. Wafer-scale 2D films, stable quasi-2D semiconductors, passivated interfaces, and controllable defect engineering are needed to improve uniformity and reliability [171]. Scalable manufacturing is also essential. Direct growth, low-damage transfer, patterned integration, and back-end-compatible processing will determine whether 2D devices can be integrated with CMOS circuits. Hybrid 2D-CMOS integration is especially important because practical visual ISC requires pixel selection, signal amplification, analog-to-digital conversion, memory access, and peripheral control [172].

Hardware-algorithm co-design will become increasingly important. Device nonidealities such as drift, nonlinear conductance update, pixel variation, and readout noise cannot be fully removed at the material level. Algorithms should therefore be designed to tolerate and compensate for these nonidealities. Calibration, normalization, adaptive training, and hardware-aware neural networks can improve system robustness. Artificial intelligence (AI) can also assist materials screening, device parameter optimization, array calibration, and task-specific architecture design [173, 174]. In this direction, the goal is not to make devices behave like ideal digital

components. Instead, the device dynamics should be matched with the target visual task.

A standardized benchmark system is needed to evaluate future visual ISC devices and arrays. At the materials level, important metrics include film uniformity, wafer-scale yield, environmental stability, and processing temperature. At the device level, response time, recovery time, retention time, endurance, energy per event, dynamic range, and conductance-state number should be reported. At the array-level, pixel yield, device-to-device variation, crosstalk, signal-to-noise ratio, readout noise, and array size are essential. At the system level, latency, total power consumption, task accuracy, robustness under noise, and real-scene performance should be evaluated. These metrics should be reported under clear testing conditions, including wavelength, light intensity, pulse width, bias voltage, readout scheme, and array scale.

Reliability and reproducibility should receive more attention. Many studies still report the best response from selected devices [175]. This is not sufficient for deployable visual ISC. Future reports should include statistical distributions of photoresponse, retention, energy consumption, and cycle-to-cycle variation. Array-level demonstrations should provide uniformity maps, yield statistics, and performance changes after repeated optical or electrical programming. For visual tasks, accuracy alone is not enough. A system with high accuracy but high latency or high power may not be suitable for edge vision. Conversely, a low-power system must still maintain acceptable robustness under motion, noise, illumination change, and background interference.

Overall, deployable 2D optoelectronic visual ISC will require coordinated advances in materials, devices, arrays, circuits, and algorithms. Materials must be uniform and stable. Devices must provide controllable plasticity and reliable retention. Arrays must be scalable and addressable. Circuits must support low-noise and low-power readout. Algorithms must adapt to device dynamics and real visual scenes.

With progress in advanced materials, scalable manufacturing, hybrid 2D-CMOS integration, AI-assisted co-design, and reliability standardization, 2D optoelectronic neuromorphic systems may move from laboratory demonstrations toward practical low-power visual intelligence.

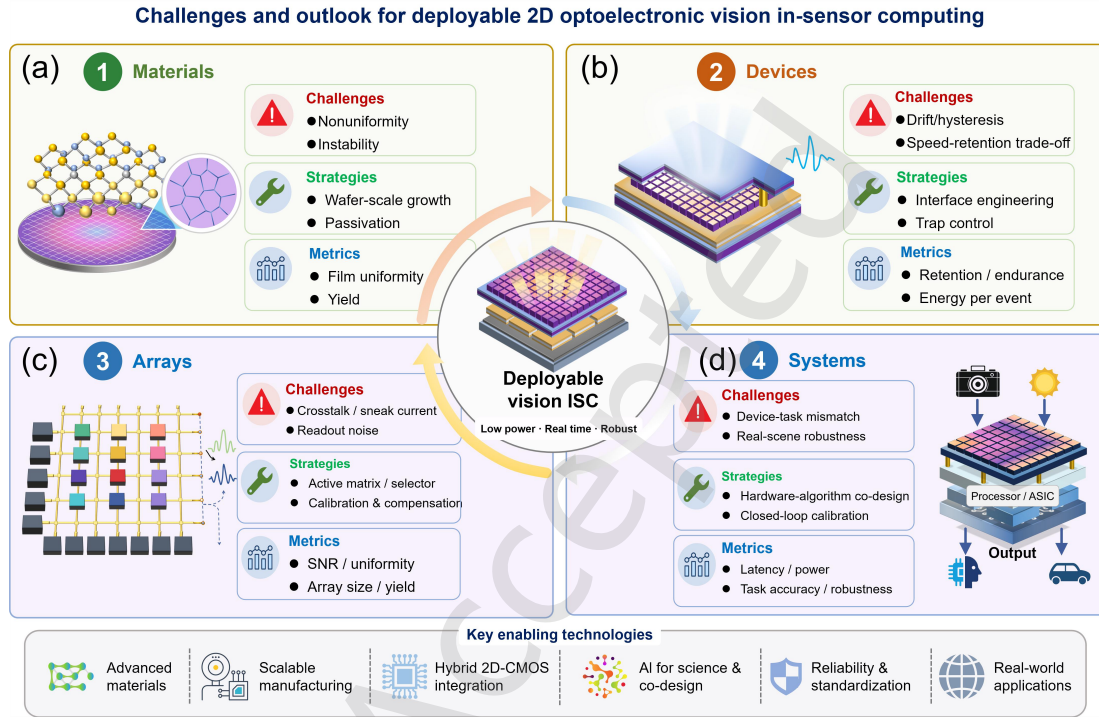


Figure 10 Challenges and outlook for deployable 2D optoelectronic visual ISC. (a) At the materials level, nonuniformity and instability remain key challenges, requiring wafer-scale growth, passivation, and improved film uniformity and yield. (b) At the device level, drift, hysteresis, and the speed-retention trade-off should be addressed through interface engineering and trap control. (c) At the array-level, crosstalk, sneak current, and readout noise call for active-matrix/selector designs, calibration, and compensation strategies. (d) At the system level, device-task mismatch and real-scene robustness require hardware-algorithm co-design and closed-loop calibration.

8 Conclusion

In summary, 2D material-enabled optoelectronic neuromorphic devices provide a promising platform for visual ISC by integrating optical sensing, conductance

modulation, memory, and front-end processing. Their functions arise from strong light-matter interaction, tunable interfaces, defect and trap states, ionic dynamics, and anisotropic photoresponse. These characteristics should be matched with specific visual tasks. Fast response and rapid recovery generally favor real-time sensing and motion perception. Controlled trapping and persistent photoconductivity support temporal integration and memory-assisted preprocessing. Tunable band structures and heterointerfaces are suitable for spectral perception. Anisotropic responses support polarization-sensitive vision. Stable multilevel conductance modulation is important for feature weighting and analog processing. Device design should also consider retention, reversibility, noise, uniformity, and array compatibility. Current studies have progressed from single-device demonstrations to arrays and visual tasks. Large-scale integration and real-scene validation remain limited. Future work should focus on scalable material growth, stable interfaces, reliable arrays, standardized benchmarking, and hardware-algorithm co-design. These advances will support the development of scalable, reliable, and energy-efficient visual ISC systems.

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.

Declaration of competing interest

There are no conflicts to declare.

Acknowledgement

This work was supported by the NSFC (12474071), Natural Science Foundation of Shandong Province (ZR2025QB50, ZR2025ZD10, ZR2024YQ051), Taishan Scholar Foundation of Shandong Province (tsqn202507058, tsqn202408006), Guangdong Basic and Applied Basic Research Foundation(2025A1515011191), funded by Basic

Research Program of Jiangsu (BK20250420, BK20240424), Open Research Fund of State Key Laboratory of Crystal Materials (KF2406), Young Talent of Lifting engineering for Science and Technology in Shandong, China (SDAST2024QTB002), and the Outstanding Young and Middle-aged Scholar Program of Shandong University. The authors acknowledge Key Laboratory of Computational Neuroscience and Brain-Inspired Intelligence (Fudan University), Ministry of Education.

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