2D Materials

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Perspectives on 2D materials for hybrid and beyond-Si image sensor applications

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Keywords: image sensor, two-dimensional material, 3D integration, neuromorphic photodetector, in-sensor computing, curved sensor

Abstract

The complementary metal–oxide–semiconductor (CMOS) image sensor has become essential and ubiquitous in our daily lives as it is present in almost every pocket. As demand for compact, multifunction, and high-efficiency Internet of Things applications continues to rise, novel configuration designs and manufacturing methods, such as neural network integration and 3D stacking have been implemented to enhance the CMOS image sensor's (CIS) performance. However, the progress of image sensors based on silicon CMOS technology would eventually be limited by the intrinsic optical, electrical, and mechanical properties of silicon material. This has led to the exploration of two-dimensional materials (2DMs) and the emergence of 2DMs as promising candidates for the next generation of optoelectronic devices. In this article, we discuss the current advancements and challenges associated with silicon CISs and the potential benefits of incorporating 2DMs in the image sensor. We highlight three critical opportunities for 2DMs, including Si CMOS/2DMs hybrid structure and direct growth techniques of 2DMs on Si for back-end-of-line integration, 2DMs-based neuromorphic photodetectors (PDs) and optical neural networks for in-image-sensor-processing, and curved image sensor based on 2DMs PDs for bionic detection. With the growing maturity of 2DM technologies, we anticipate that the device scaling and the increase of integration density of 2DM electronics in the image sensor will continue, leading to the development of highly efficient, compact, intelligent, and versatile 2DM image sensors in the near future.

1. Introduction

Vision is widely regarded as the most crucial sense among the five senses of the human being. Over 80% of the external information from the environment is processed through the visual pathway [1]. The image sensor is the key component for obtaining visual information. In humans, the visual signal is first converted into potential pulses by photoreceptor cells (rods and cones) in the retina and then transmitted through the optical nerve to the brain for processing. When it comes to imaging electronics such as digital cameras, photosensitive devices like photodiodes and phototransistors are used to convert light into electrical current. Over the past two decades, complementary metal–oxide–semiconductor (CMOS) image sensor (CIS) based on silicon photodiode array and metal–oxide–semiconductor field-effect transistor (FET) signal processing circuit has emerged as the market-dominating device over the conventional charge-coupled device due to its faster readout speed, lower power consumption, cost-effectiveness, and scalability [2]. In recent years, new device configuration and integration technologies, such as back-illuminated CIS (BI-CIS) and 3D chip integration, have been pushing the frontiers of the performance and industrial productivity of CIS [3, 4]. Nevertheless, the further progress of CIS is limited by the low photoresponsivity (hundreds of mA W^{-1}) of silicon-based photodetectors (PDs) due to the intrinsic indirect bandgap of silicon [5]. Also, silicon PD cannot provide satisfying photoresponsivity beyond the Vis-NIR wavelength range [6], which limits its application other than photography. Additional restrictions, such as untunable photoresponsivity and mechanical rigidity of silicon photodiode further hinder the implementation of CIS as the intelligent edge computing device and the wearable and implantable device.

The use of two-dimensional materials (2DMs) presents a promising path toward developing a new generation of image sensors with unique properties that complement the current CIS technology and even surpass it. Graphene was the first 2DM to be discovered and was quickly utilized in photonics and optoelectronics [7]. This trend has continued with the discovery of other 2DMs, such as transition metal dichalcogenides (e.g. MoS_2, WSe_2), hexagonal boron nitride (h-BN), and black phosphorus (BP), each of which possesses unique electrical and optoelectronic properties, including strong light-matter interaction, tunable bandgap, broadband light absorption, van der Waals integration and outstanding mechanical flexibility [8–13]. Furthermore, the recent advancements in low-temperature wafer-level deposition techniques of 2DMs hold great promise for fulfilling their industrial potential for back-end-of-line (BEOL) integration. From another aspect, the structure and function of the biological photoreceptors in human vision system have inspired the development of 2DM neuromorphic PDs, which exhibit retina photoreceptor-like, reconfigurable photoresponsivity or photoconductance and memory in response to optical and electrical stimuli. These neuromorphic PDs can effectively encode spatiotemporal optical information and empower optical neural network (ONN) with in-image-sensor analog computing capability while consuming low power similar to biological vision system.

In this perspective article, we introduce the advancements of silicon CIS, the challenges to manufacturing and performance improvement, and explore how the use of 2DMs in CIS can help. Unlike other reviews that solely introduce the growth of 2D materials or their applications in neuromorphic devices, we systematically approach this topic from the properties of 2D materials. We discuss their compatibility with traditional semiconductor processes; due to the physical properties of 2D materials, they can effectively fulfill the role of sense-memory-compute integrated devices; owing to their unique mechanical properties, they are well-suited for realizing curved image sensors [14–16]. Specifically, this is followed by a description of the wafer-level deposition methods of 2DM to manifest its feasibility for large-scale, industrial-compatible production. Next, we discuss the 2DM neuromorphic PDs with concurrent optical sensing and memory functions. Emphasis is made on explaining how the neuromorphic PDs can be applied in ONNs and tackle challenging detection tasks that are difficult for conventional CIS. Furthermore, we discuss the advantages of curved image sensors over planar sensors and explore the methods of fabricating 2DM curved image sensors with small curvature radius similar to that of the human retina. Lastly, we suggest directions for further advancements of 2DM image sensors in terms of pixel scaling, homogeneous device integration, and multilayer 3D monolithic stacking. Our article concludes with a glimpse of image sensors based on 2DMs for the future. The outline of this article is depicted in figure 1.

2. Evolution of CIS and opportunities for Si/2DMs hybrid image sensor

2.1. CIS and its progress

CIS was first demonstrated almost 30 years ago and has now become ubiquitous [26]. The conventional CIS is front illuminated (FI-CIS), where the microlens, color filter, and interconnecting metal wire sit on top of the photodiode. Compared with FI-CIS, the BI-CIS is featured by arranging photodiode layer above the metal wiring layer [17]. This configuration increases the light capture area by eliminating the blockage of opaque metal wires. Additionally, it achieves higher sensitivity and wider optical angular response by reducing the distance between the microlens and the light-receiving surface [27]. Silicon-on-insulator (SOI) technology has been utilized to make stacked BI-CIS through wafer bonding [28, 29]. In SOI, the photodiodes array is fabrication on top silicon layer, and SOI wafer is then flipped and bond with bottom CMOS integrated circuit (IC) wafer. In such case, the top silicon layer and substrate need to be as thin as possible to reduce unwanted light absorption [30]. Thinning the silicon wafer can make it fragile. Moreover, BI structure and fabrication processes can cause multiple issues such as decreased signal-to-noise ratio, increase in dark current, long-term reliability degradation, increased manufacturing complexity and high costs [31].

2.2. CMOS/2DMs hybrid image sensors and 2DMs heterostructure

Unlike conventional BI-CIS technology using flip-chip and wafer bonding methods, 2DM can be transferred to the surface of CMOS wafer at ambient temperature and pressure, allowing the feasible and efficient monolithic integration with silicon IC to realize BI-CIS. Additionally, the ever-growing family of 2DMs can provide a library of materials with distinct electrical and optoelectronic properties to choose from, which can potentially customize the functionality of image sensor [32]. In figure 2(a), a 388 × 288 PDs array based on transferred CVD-grown graphene and light-sensitive PbS colloidal quantum dots (CQDs) on CMOS readout circuit has been demonstrated with broad detecting wavelength range from 300–2000 nm [20], exceeding the upper

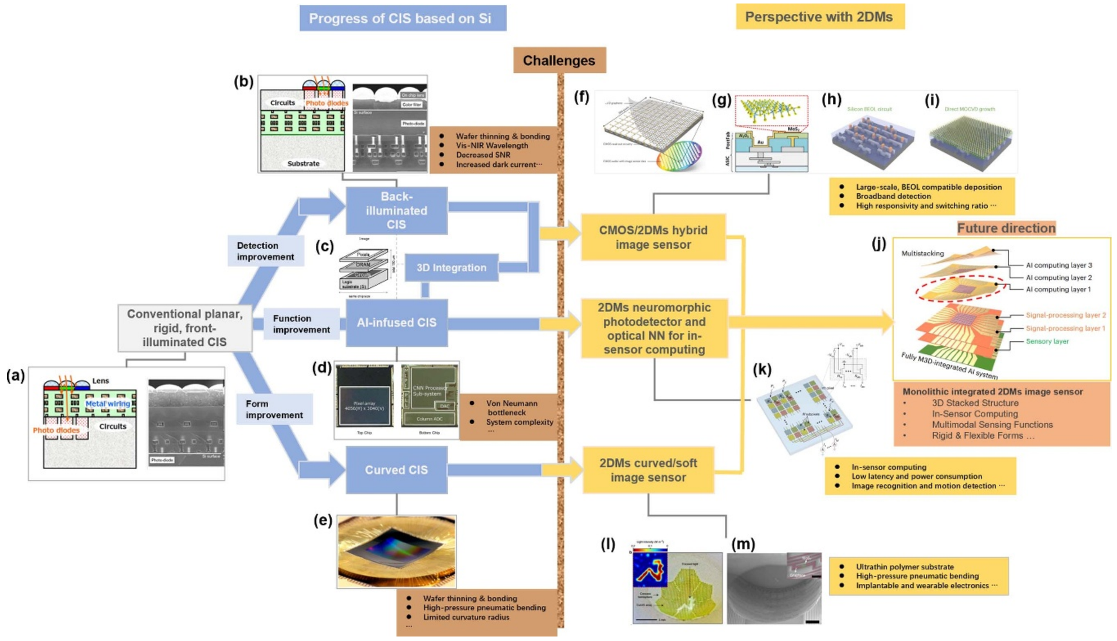

Figure 1. Evolution of CMOS image sensor, challenges to manufacture and performance improvement and opportunities for 2D materials. (a) Left: © [2019] IEEE. Reprinted, with permission, from [3]. Right: © [2006] IEEE. Reprinted, with permission, from [17]. (b) Left: © [2019] IEEE. Reprinted, with permission, from [3]. Right: © [2006] IEEE. Reprinted, with permission, from [17]. (c) © [2019] IEEE. Reprinted, with permission, from [3]. (d) © [2021] IEEE. Reprinted, with permission, from [18]. (e) Reproduced from [19]. CC BY 4.0. (f) Reprinted with permission from [20]. Copyright (2017) American Chemical Society. (g) Reprinted with permission from [20]. Copyright (2017) American Chemical Society. (h), (i) Reprinted with permission from [22]. Copyright (2023) American Chemical Society. (j) Reproduced from [14], with permission from Springer Nature. (k) Reproduced from [23], with permission from Springer Nature. (l) Reproduced from [24], with permission from Springer Nature. (m) Reprinted with permission from [25]. Copyright (2021) American Chemical Society.

limit of traditional silicon photodiode [33]. The photogenerated carrier separation can benefit from the high mobility of graphene, thus leads to high responsivity over 10^7 A W^{-1}, and the semimetal nature of graphene can suppress the $1/f$ noise, which results in high detectivity over 10^{12} Jones. Besides, 2DMs with proper bandgap can also serve as the channel material for the optoelectronic device. Monolayer MoS_2 has a direct bandgap of 1.8 eV, making it efficient at absorbing visible light [34]. Heterogeneous integration of MoS_2 phototransistors array with CMOS readout circuit has been demonstrated previously [21, 35]. As shown in figure 2(b), recent research from Harvard university and Samsung Inc. reported a high resolution, 200 × 256 MoS_2 phototransistors array with integrated CMOS time-to-digital converter circuit. The image sensor exhibits low dark current of 670 fA and large switching ratio of 76 dB [21]. More interestingly, detection spectrum of the PD can also be expanded through van der Waals heterogeneous integration of 2DMs with different optical and electrical properties. In the family of 2DMs, BP is considered as a promising material for infrared sensing because of its direct, thickness dependent bandgap of 0.3 eV (bulk) to 2.0 eV (monolayer) and high carrier mobility up to 1000 $cm^2\ V^{-1}\ s^{-1}$ [10]. BP-MoS_2 heterojunction PD has been demonstrated with high external quantum efficiency (EQE) of ∼30%–35% at MWIR spectral range ($\lambda = 2.5$–$3.5\ \mu m$) and peak detectivity of 1.1×10^{10} Jones at $\lambda = 3.8\ \mu m$ [36]. Conventional MWIR PDs based on heterogeneous integration of II–VI HgCdTe and III–V InGaAs materials with silicon generally require costly deposition method and active cryogenic cooling. In comparison, 2DM-based MWIR PD shows elevated performance and has less processing and operating constrains [37].

2.3. Wafer-scale, BEOL-compatible deposition of 2DMs

One of the prominent advantages of low-dimensional material is its wafer-scale, low-temperature, BEOL-compatible (<400 °C) deposition. A 16-bit microprocessor was built with over 14 000 CMOS carbon nanotube (CNT) FETs, where the CNTs are deposited on wafer using low-temperature, solution-based process [38]. In recent years, solution-based manufacturing has been extensively investigated and adopted across various fields, including micro/nano-electronics, optoelectronics, biomedical devices, and soft electronics owing to its cost effectiveness, scalability, and rapid prototyping [39–44]. However, deposition of high-quality 2DMs at low temperature is a challenge due to the introduction of wrinkles, contamination and defects during the mainstream transfer process [45, 46]. Clean transfer method has been developed with metal-assisted transfer and protection [47], but whether it can eliminate all the artifacts

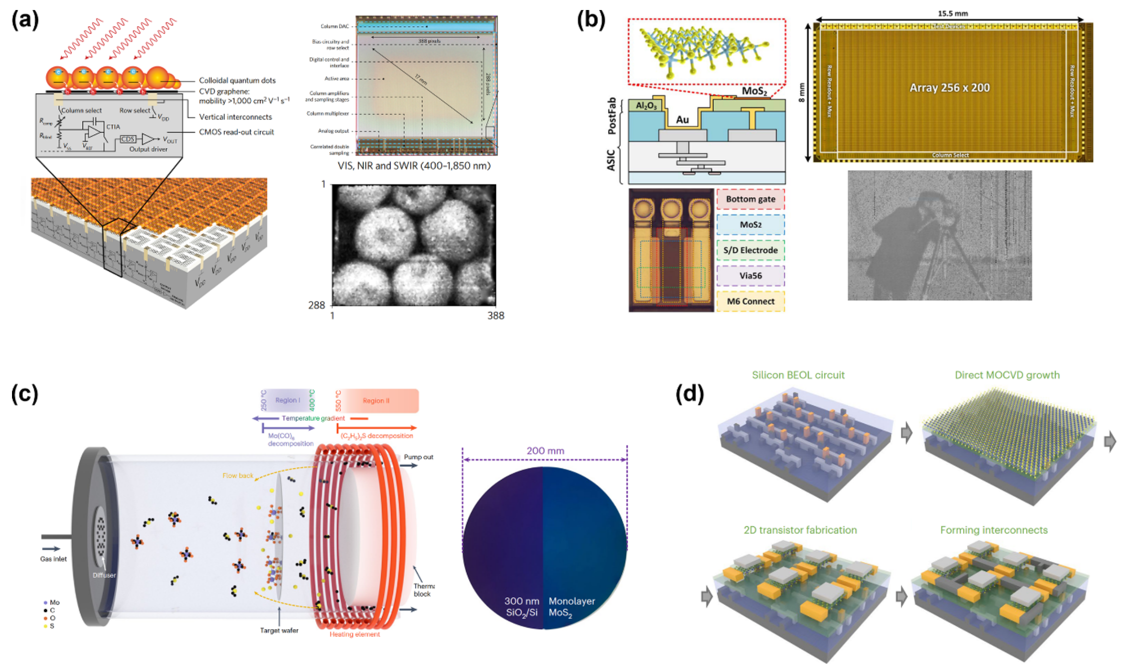

Figure 2. Si CMOS/2DMs hybrid BI-CIS image sensors and BEOL-compatible direct growth of 2DM on Si surface. (a), (b) Schematic illustration, chip microscopic photograph and sensor-captured photograph of BI-CIS CMOS/2DMs hybrid image sensors with (a) graphene/PbS CQDs photodetectors. Reprinted with permission from [20]. Copyright (2017) American Chemical Society. (b) Monolayer MoS_2 phototransistors. © [2022] IEEE. Reprinted, with permission, from [21]. (c) Schematic illustration of low temperature (<300 °C) MOCVD growth process of monolayer MoS_2 on 200 mm Si wafer. (d) Device fabrication and CMOS integration processes on the MOCVD grown MoS_2. (c), (d) Reprinted with permission from [22]. Copyright (2023) American Chemical Society.

(such as wrinkles) and maintain the material quality in large-scale still remain a question. Recent research has proposed low-thermal budget, BEOL-compatible MOCVD growth of monolayer MoS_2 at lower than 300 °C on a 200 mm silicon wafer. The MOCVD growth process of MoS_2 and MoS_2-based device integration process with silicon BEOL circuit are depicted in figures 2(c) and (d) [22]. The deposition temperature of crystallinity monolayer MoS_2 can be further reduced to around 150 °C, which renders the direct deposition of MoS_2 on flexible polymer substrates possible [48]. A 6 × 6 phototransistors array is fabricated based on the low-temperature deposited MoS_2, and high photoresponsivity of 50 A W^{-1} is achieved at 405 nm laser irradiation, suggesting the outstanding material quality of the grown MoS_2 for image sensor application.

3. 2DM image sensors for beyond Si CMOS technology

3.1. AI-infused CISs and neuromorphic PDs based on 2DMs

In the recent Internet of Things era, the influx of unprocessed images has posed significant challenges to computing systems, with frequent data shuffling between modules inevitably leading to high power consumption. Additionally, the technological gap between memory and microprocessors exacerbates physical separation, causing interconnect resistance mismatches and increased training latency. To address these issues, in-memory computing based on resistive switching materials has shown promise. The integration of memory and computing eliminates redundant data shuffling between modules, thus fundamentally subverting the von Neumann architecture. This illustrates how AI can enhance the physical implementation of traditional computing units. Specifically, memristors, which use electrical channels to achieve multiple resistance states, facilitate major neural network workloads through matrix calculations.

Compared to electrical channels, optical channels inherently provide multi-dimensional information. Optical processors and optoelectronic devices offer low latency, high bandwidth, and low energy consumption [49, 50]. Consequently, driven by electrical integration, the potential integration across sensing, memory, and computing could enable unique performances and applications beyond the reach of electronic devices. However, in typical processing system designs, sensors are usually physically separated from memory and computing units. Due to significant incompatibilities in the growth process, the mainstream method to integrate sensing materials and peripheral circuits is through flip-chip technology using indium columns. This heterogeneous integration presents challenges related to impedance matching and power management [18]. To tackle these challenges, the concept of 'in-sensor computing' or 'near-sensing computing' has been proposed, requiring sensing materials to exhibit memristor-like behavior to encode optical information. Nevertheless, given the constraints of energy conversion efficiency and single-layer perception methods, balancing energy loss and recognition accuracy remains a notable challenge. Devices based on this paradigm face inherent obstacles in deep neural network implementations. As a result, the importance of these sensing materials in complex image processing applications is diminishing. Instead, they are being favored for retina-like preprocessing functions, such as convolution, while leaving the task of the fully connected layer to peripheral computational arrays. This encapsulates the concept of AI-infused CISs and neuromorphic PDs [51, 52]. In such a case, single-element image sensor with intrinsic sensing and in-memory computing ability is potentially a more favorable solution. Neuromorphic PDs, which inspired by photoreceptor cells and neurons in the biological retina, have been widely studied and demonstrated with non-volatile memory and reconfigurable photoresponsivity states or photo-induced conductance states [53, 54]. These discrete states can be treated as synaptic weights in the artificial neural network and be used to carry out computational tasks. Due to the strong light-matter interaction, electrical and optical tunability and availability of defect engineering, 2DMs are found to be favorable for neuromorphic optoelectronics applications [54, 55].

3.2. Mechanisms and performances of 2DM neuromorphic PDs

The modulation mechanisms of the reconfigurable photoresponsivity or photoconductance in 2DM neuromorphic PDs differ based on the device's material selection, treatment, and structure design. Imperfection-facilitated resistive switching has been widely reported in 2DMs memristive devices [56, 57]. Recent research reported neuromorphic PDs based on plasma-treated MoS_{2-x}, as illustrated in figure 3(a). Figures 3(b) and (c) shows the photocurrent intensity and polarity can be tuned with electrical programming pulses, which are mainly due to the induced migration of sulfur vacancies and Schottky barrier height modulation. Eleven discrete photoresponsivity states were achieved with designed electrical pulse stimulation scheme, and object detection with high accuracy of 97% was reached by building a convolutional neuromorphic network based on the reconfigurable, non-volatile photoresponsivity states of the device [58]. On the other hand, charge trapping centers, such as floating gate or interfacial trapping states, can also enable light-induced memory by storing photogenerated electrons/holes even after the removal of light stimulus [59, 60]. In figures 3(d) and (f), a multibit, non-volatile optical memory based on MoS_2/BN/graphene was reported with 18 discrete current states [61]. High switching ratio over 10^6 and responsivity over 10^4 A W^{-1} were also achieved. By utilizing graphene as floating gate, the device can either be programmed (to high resistance state, HRS) by electrical injection of electrons into the graphene or erased (to high low resistance state, LRS) with tunneling of photogenerated holes (in MoS_2) through MoS_2/h-BN to recombine with the electrons in the floating gate (figure 3(e)).

3.3. 2DM neuromorphic PDs in ONN for in-sensor computing

As shown in figures 3(g) and (h), to realize in-sensor computing, neuromorphic PDs are typically arranged into a crossbar array to create artificial ONN. Vector matrix multiplication (VMM) is considered as the key operation in deep learning algorithms. While VMM in AI-infused CIS needs to be facilitated by convolutional neural networks [62], the ONN based on neuromorphic PDs can perform VMM in situ without the need of external circuits. To be more specific, the multiplication operation is done in the transduction process as the photocurrent is the product of photoresponsivity and incident light intensity, and the accumulation operation is carried out by collecting current at the terminal of parallel connected pixels, according to Kirchhoff's law [23]. Figure 3(i) demonstrates that the ONN could carry out simple classification tasks with different input images of letters.

3.4. Motion detection and recognition on 2DM-based ONN

The memory-infused neuromorphic PDs and ONN are also featured by the ability to tackle complex detection problems that traditional image sensors struggle to handle. Motion detection and recognition has long been a research hotspot and a challenging task for machine vision [63]. It is especially important for critical applications such as patient monitoring, fire and smoke detection, surveillance, and traffic control [64–67]. The output of conventional CIS is in the form of static frame, which lacks of temporal information. The detection of dynamic movement cannot be achieved in conventional CIS without costing considerable computing and data storage resources. However, using 2DM neuromorphic PD, the image sensor can incorporate spatial and temporal information due to its intrinsic memory. A retina-inspired, highly compact, motion detection and recognition image sensor based on 2DM heterostructure (BP/Al_2O_3/WSe_2/h-BN) neuromorphic PDs was demonstrated [68]. The polarity and intensity of the photocurrent of the device can be modulated by electrical and optical pulses in a non-volatile way. The ONN stores the conductance

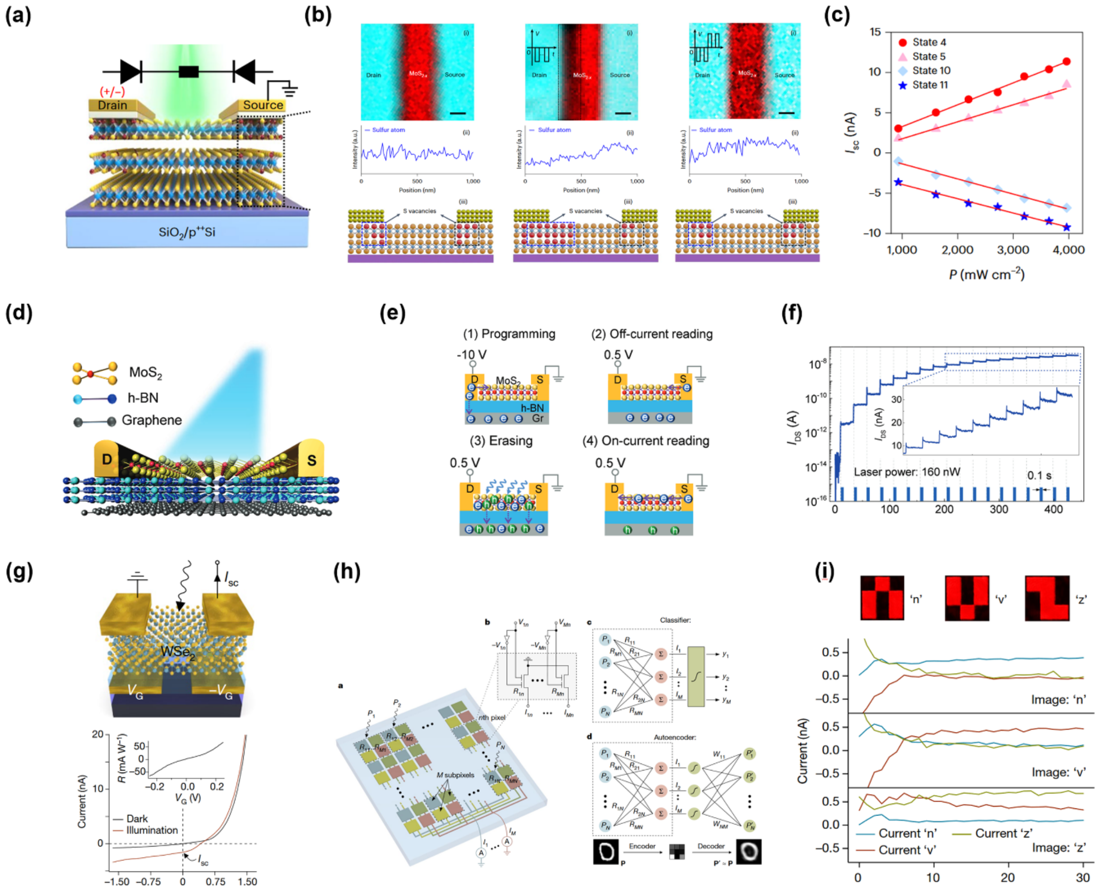

Figure 3. 2DMs neuromorphic photodetectors PDs and optical neural network as in-sensor computing system for AI-infused image sensing. (a) Schematic illustration of reconfigurable neuromorphic PD based on plasma-treated multilayer MoS_{2-x}. (b) Mechanism of reconfigurable photoconductance programming based on migration of sulfur vacancies. (c) Functions of I_{sc}–P (optical power density), showing discrete photoconductance states with both positive and negative polarity. (a)–(c) Reproduced from [58], with permission from Springer Nature. (d) Schematic illustration of floating gate neuromorphic PD based on MoS_2/hBN/graphene heterostructure. (e) Operations of the neuromorphic PD as non-volatile optical memory cell. The programming process modulates the device into high resistance state (HRS) and the light-induced erasing process modulates the device into low resistance state (LRS). Graphene serves as the charge trapping center for electron storage and photo-induced electron-hole recombination. (f) Multibit optical memory with 18 discrete conductance states programmed by light signal. (d)–(f) [61]. John Wiley & Sons. © 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (g) Schematic illustration of WSe_2 neuromorphic PD with gate tunable photoresponsivity. (h) Optical neural networks consist of neuromorphic PDs for computational tasks such as classification and encoding. (i) Classification results of different projected letter images. (g)–(i) Reproduced from [23], with permission from Springer Nature.

states in the neuromorphic PD array as the synaptic weights, represented by positive and negative conductive matrix. The mechanism of motion detection is illustrated in figure 4(a). Two frames of image (each contains $m \times n$ image pixels) at different moments are multiplied with $m \times n$ positive and $m \times n$ negative conductive matrix respectively, and summed. The operation will output distinguishable moving and static profiles of image pixel brightness distribution, as shown in figure 4(b), which can be further processed to remove static background and highlight the moving object. Compared with conventional CIS for motion detection and recognition, which requires combination of different circuit modules, the all-in-one 2DM image sensors realized excellent motion detection and recognition performances of 100% separation detection of moving objects and fast recognition at only four training epochs at 10% noise level. Motion detection and recognition image sensor with similar WSe_2/h-BN heterostructure and bottom gate also exhibits light-induced non-volatile memory due to the trapped photogenerated interfacial charges between the h-BN and Al_2O_3 layer [69]. Different motion modes, such as uniform linear motion, acceleration and rotation can lead to unequal exposure time of the moving object to the image sensor array, resulting in differentiable, spatiotemporal information-encoded current map of the sensor array. A perceptron was implemented based on the neuromorphic PD array and motion mode recognition accuracy achieve 100% with short training of 10 epochs.

Artificial neurons and synapses are characterized by both long-term plasticity (non-volatile memory) and short-term plasticity (STP). STP includes phenomena such as paired pulse facilitation (PPF) and

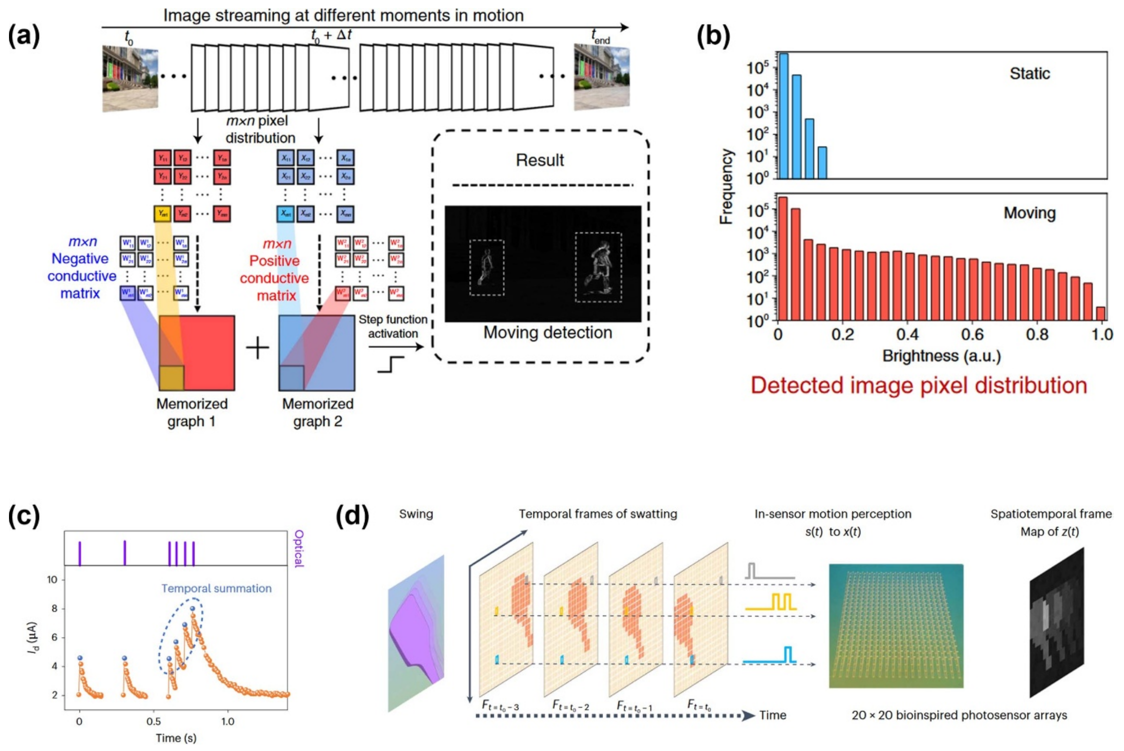

Figure 4. Motion detection mechanisms of ONNs based on neuromorphic PDs with long-term plasticity (LTP, non-volatile memory) and short-term plasticity (STP). (a) Mechanism of motion detection with LTP neuromorphic PDs. Two sets of $m \times n$ image pixels at different times are multiplied with $m \times n$ positive and negative conductive matrix (where the conductance states are stored as synaptic weights) respectively and summed, which results in (b) distinguishable static and moving profiles of image pixel brightness distribution that can be further processed to detect movement. (a), (b) Reproduced from [68], with permission from Springer Nature. (c) STP of neuromorphic PDs. The STP is characterized by the paired pulse facilitation (PPF) effect, where smaller time interval Δt between two consecutive optical pulses would lead to larger photocurrent response of the device to the 2nd optical pulse. (d) Utilization of PPF effect to encode the temporal information and enable the detection of motion direction. (c), (d) Reproduced from [70], with permission from Springer Nature.

paired pulse depression, which are effective for encoding temporal information. For example, in STP neuromorphic PDs, PPF refers to the enhanced photocurrent response to a second optical stimulus pulse when it follows closely after the first pulse. The degree of this enhancement is closely related to the time interval (Δt) between the two pulses, as shown in figure 4(c) [71–73]. For PPF, smaller Δt will lead to larger photocurrent response. In such a case, the temporal information can be directly programmed into the amplitude profiles of photocurrent responses, makes it feasible for fast motion detection. A prototype motion detection ONN is constructed based on MoS_2 phototransistors array, which is capable of mimicking the functions of graded neurons in the eyes of insect [70]. The biomimicking graded neuronal function originates from the trap/release of charges from shallowing trapping states in MoS_2 phototransistor. As illustrated in figure 4(d), the temporal information can be encoded as the optical pulse interval and later be received and processed by the STP neuromorphic PD arrays through the utilization of the PPF effect. The ONN image sensor can effectively detect the proximity and moving speed of the object. It reached outstanding information transmission rate at 1200 bit s^{-1} and recognition accuracy of 99.2%.

3.5. 2DMs image sensor in soft and curved form

For bionic image sensor, the faithful imitation of the retina demands not only replicating its sensory and neural functions, but also its form factor, that is, curved. Compared with rigid, planar image sensor, curved image sensor can bring several advantages. For camera with wide angles and field of view, curved image sensor can mitigate distortion and vignetting [74], which consequentially reduces the number of lenses required for optical aberration correction and simplifies the optical design. In addition, with reduced angle of incidence, curved image sensor can optimize light absorption by efficiently gathering photons across its entire surface, including edges. This enhanced capability results in better performance in low-light conditions, a broader dynamic range, and an improved signal-to-noise ratio. Previous report has demonstrated curved CIS by die thinning and application of pneumatic pressure [19]. However, the permissible curvature is still limited by the strength and stiffness of silicon, which constrains its conformality to arbitrary surfaces, making it unsuitable for wearable or implantable imaging devices such as artificial retina. Thanks to the excellent mechanical robustness of 2DMs, image sensor with large curvature can be

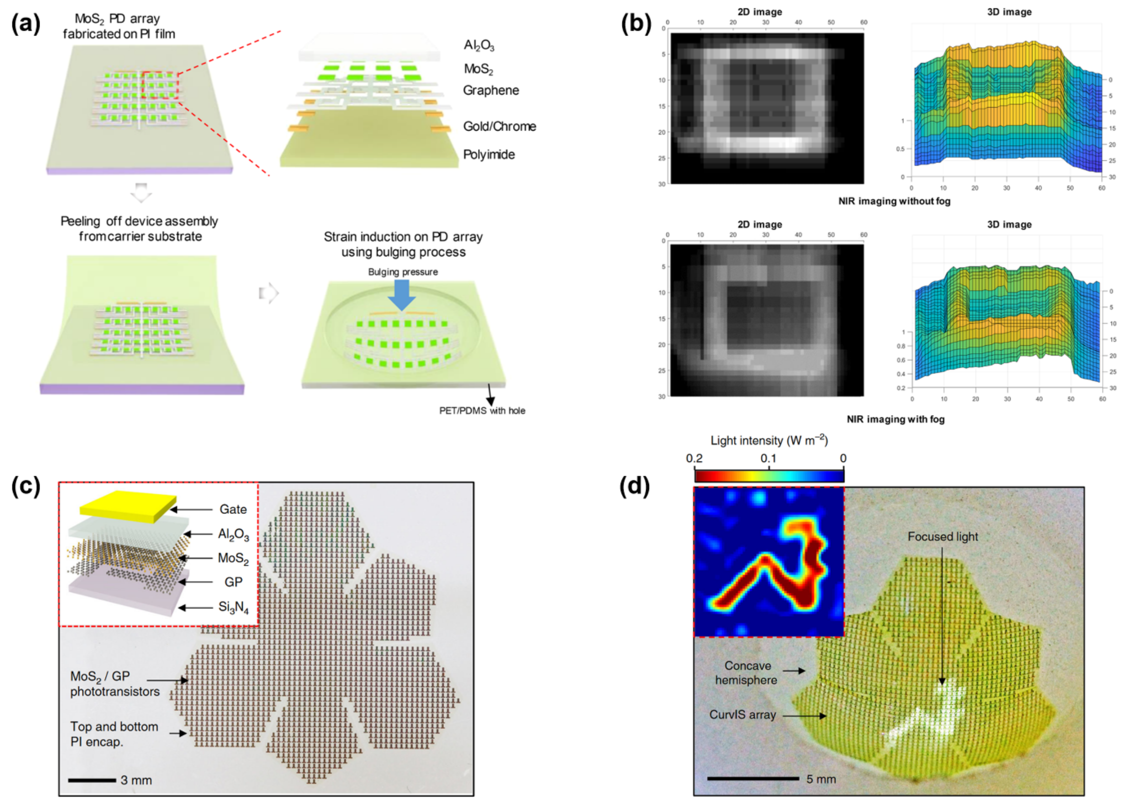

Figure 5. 2DM curved image sensors with designed substate and configuration. (a) Illustration of the fabrication process of curved MoS_2/graphene PD array on ultrathin polyimide substrate. (b) NIR imaging at ambient and foggy conditions. (a), (b) Reprinted with permission from [25]. Copyright (2021) American Chemical Society. (c) The precut truncated icosahedron shaped MoS_2/graphene phototransistors array. (d) Assembled hemispherical curved image sensors array and captured images (inset). (c), (d) Reproduced from [24], with permission from Springer Nature.

feasibly realized with proper substate and designed configuration [24, 25, 75, 76]. Fabricated on ultrathin polyimide (∼6 μm), MoS_2/graphene PDs array can sustain biaxial strain of 1.19% and can be curved into hemispherical shape with curvature radius of 6 mm through a pneumatic bulging process, as illustrated in figure 5(a) [25]. The curved sensor is also capable of NIR imaging. Figure 5(b) shows the results of NIR imaging at ambient and foggy conditions. Inspired by the art of paper folding, an origami design, hemispherically curved image sensor array was also reported [24]. The MoS_2/graphene PDs array on planar flexible polyimide substrate was precut into truncated icosahedron (figure 5(c)) and assembled into 3D hemispherical structure by folding (figure 5(d)), similar to the splice of the soccer ball. This designed configuration can isolate the PDs from strain and prevent the potential damage to the devices. The curvature radius of the curved image sensor array is 11.34 mm, which is close to that of the human retina. The in-sensor processing capabilities, as we discussed previously, can also be realized with soft 2DM neuromorphic image sensors [75]. The development of curved image sensor is an important progress toward faithful imitation of human visual recognition system in both form and function. This technology can potentially find its application in soft robotics and neuroprosthetics.

4. Outlook and vision

Despite the great progresses made on CMOS/2DMs hybrid image sensor and neuromorphic image sensor, 2DMs can further propel the level of the device scaling and integration into new heights. For image sensor based on silicon or on 2DMs, the scaling of pixel size has been the driving force behind product innovation. Compared with state-of-art high-resolution CIS, which has reached 200 M pixels with pixel size reaching submicron level [77, 78], the reported image sensors array based on 2DMs have pixel dimension of tens of microns and resolution less than 1 M pixel [20, 21, 24, 79], which is partially due to the poor light absorption and short carrier lifetime of 2DMs. However, the dangling-bond-free surface of 2DMs allows the van der Waals integration of different materials to compensate for those shortcomings [80]. Another limitation of the shrinking of 2DM-based pixel dimension is due to the immature nanofabrication processes compared with the mature silicon CMOS technology. Sub-micron sized MoS_2 phototransistor has recently been demonstrated with an active area of only 0.0065 μm^2 [81], suggesting that there is no fundamental obstacle behind the scaling of 2DMs image sensor. As 2DMs being the promising candidate for next-generation semiconductor materials beyond Moore's law [82, 83], the evolving scaling technology of 2DM FET can potentially be migrated in making large-scale, high-resolution 2DM image sensor with smaller pixel size.

2DMs are already known for their remarkable optical and electronic properties, rendering the homogenous, monolithic integration of all 2DMs-based electronics possible, which can potentially reduce the impedance mismatching among devices and lower the power consumption. Previous studies have demonstrated 1P-1T pixel structure [84] as well as homogenous integration of phototransistor and analog processing circuit all based on MoS_2 [85]. Substantial progress has been made in 2DM electronics recently in terms of integration density and 3D stacking capability. Monolithic 3D integration of six layers of 2DMs-based transistors and memristors arrays was enabled by large-area, bottom-up material exfoliation and transfer method, and since the fabrication and connection of the layers requires not functional participation of silicon wafer, the 3D chip can be made on flexible substrate [14, 86]. What is more, wafer-scale neural network circuit containing 32 × 32 floating gate FET array has also been demonstrated for VMM operation and parallel processing. With the steady progress of 2DMs in very large-scale integration technology, we can expect the logic unit to be incorporated in 2DMs image sensor in the short future [83, 87].

The convergence of recent developments in technology has paved the way for a promising future in the realm of image sensors based on 2DMs. By integrating sensing, memory, signal processing, logic computing, and neuromorphic analog computing functions into a compact, 3D-stacked thin film, it is possible to envision a highly efficient image sensor that offers low power consumption, high performance, broadband detection, and ubiquitous imaging and analyzing capabilities. The potential implications of such a device are vast and far-reaching, with implications for a wide range of applications in fields ranging from machine vision to biomedical imaging.

Data availability statement

No new data were created or analyzed in this study.

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