Journal of Intelligent Material
https://www.ffspub.com/index.php/jim/index
ISSN 3104-8994 (print)
E-mail: jim.office@ffspub.com

Review

Next-Generation Intelligent Wearable Systems Enabled by 2D Materials: From Atomic Mechanisms to Functional Integration

Jiayu Ma[1], Lu Jin[2], He Tian[3†], Zongmin Ma[1†]
[1]*School of Semiconductors and Physics, North University of China, Taiyuan 030051, China*
[2]*School of Future Technology, University of Science and Technology Beijing, Beijing 100083, China*
[3]*School of Integrated Circuits, Tsinghua University, Beijing 100084, China*
[†]*E-mail: tianhe88@tsinghua.edu.cn (H.T.); mzmncit@163.com (Z.M.)*

Received: December 12, 2025 / Revised: April 14, 2026 / Accepted: May 11, 2026 / Published online: May 20, 2026

Abstract: Wearable technology is rapidly moving towards intelligent, flexible, and multifunctional integration. Its core challenge lies in achieving a balance between high sensitivity, autonomous power supply, data processing, and comfortable wear under conditions of limited volume, complex deformation, and dynamic interaction. Two-dimensional (2D) materials, with their atomic-level thickness, exceptional flexibility, rich surface chemistry, and tunable electrical and optical properties, provide a revolutionary material platform for building next-generation intelligent wearable systems. This paper first describes the characteristics of 2D materials (such as graphene, transition metal dichalcogenides (TMDs), MXenes, and black phosphorus), then introduces the research progress in wearable intelligent systems, including design strategies and technical paths for 2D materials in intelligent sensing interfaces, drive structures and human-computer interaction, neuromorphic computing and flexible circuits, energy and thermal management systems, and system integration. Next, it analyzes the challenges that 2D materials will face in the future, and finally provides a systematic summary of the current application of 2D materials in wearable technology, and looks forward to future development directions.

Keywords: Two-Dimensional Materials; Wearable Electronics; Intelligent Sensing; Neuromorphic Computing; Thermal Management; Flexible Electronics
https://doi.org/10.64509/jim.11.63

1 Introduction

Facing the grim reality that the burden of chronic diseases in the world is increasing day by day, the traditional medical model is facing great challenges in dealing with long-term and continuous health management needs [1]. Under this background, wearable devices that use physical, chemical and biological sensors to mine physiological information in a non-invasive way are becoming a revolutionary alternative way, providing a brand-new solution for clinical diagnosis and life-cycle health management [2]. In the management of cardiovascular diseases, wearable devices can continuously monitor heart rate, rhythm and blood pressure fluctuation [3], and make early warning of risks such as atrial fibrillation and hypertensive crisis through AI algorithm [4, 5], so as to gain valuable time for clinical intervention; In the field of endocrine diseases, the continuous blood glucose monitor (CGM) provides real-time feedback on blood glucose trends for diabetic patients [6], helps patients adjust their diet and medication, and significantly improves their level of blood glucose control level [7]; In the aspect of nervous system diseases, the wearable ultrasound-based neuroregulatory device (MiniUlTra) provides a new long-term treatment strategy with non-invasive and high spatial resolution for neurodegenerative diseases such as Parkinson's disease [8], and assists doctors in optimizing treatment plans. In addition, in the rehabilitation of chronic diseases and daily health management, wearable devices can effectively improve patient self-management ability and treatment compliance by tracking indicators such as sleep and combining personalized health suggestions [9, 10].

† Corresponding authors: He Tian, Zongmin Ma
*Academic Editor: Zhou Li

Although wearable biosensors show great potential in personalized medicine, in order to achieve their long-term and non-inductive monitoring goal, strict technical requirements are put forward for the equipment itself: that is, it must ensure high performance and achieve extreme miniaturization and ultra-low power consumption [11]. However, the traditional silicon-based electronic device is approaching the limit of its physical size: with the continuous shrinking of feature size, the short channel effect becomes more and more obvious, which leads to the decline of the gate's ability to control the channel, the sharp increase of leakage current and the difficulty in suppressing static power consumption [12]. This physical limitation makes it a serious challenge to realize high-performance wearable biosensor by simply relying on the miniaturization of silicon-based hard electronics technology. At the same time, there is an essential mismatch between traditional hard electronic materials and soft biological tissues in terms of electrical conductivity, mechanical response, permeability and environmental adaptability [13]. Although organic or composite semiconductor films are stretchable or conformable, their electrochemical stability is often limited by the swelling characteristics of the materials, which leads to a decrease in the coupling efficiency between ion implantation and electron transport, and it is inevitable that the device performance will drift with time. The instability of this material level makes it a serious challenge to realize long-term and stable bioelectronic interface by relying solely on the bulk doping of organic semiconductor films. At the same time, the traditional organic semiconductor materials still have a certain degree of performance mismatch with the dynamic biological environment in terms of charge storage density, mechanical modulus matching, electrical conductivity and environmental tolerance [14, 15]. Therefore, exploring a new material system that can not only break through the physical size limitation, but also has excellent mechanical flexibility and environmental adaptability has become an urgent need for the development of flexible electronics in the post-Moore's Law era [16].

Since the successful stripping of single-layer graphene in 2004 [17, 18], this family has expanded rapidly. Researchers have successfully stripped from natural layered crystals and deeply studied transition metal disulfides (such as MoS_2) [12, 19], transition metal carbides and nitrides (MXenes) with both metallic conductivity and high mechanical strength, and Xenes (such as silicene and germanene) [20, 21]. These materials exhibit quantum properties and surface effects [22], which are completely different from their bulk shapes at atomic thickness, and together form a huge and multifunctional material system. As a brand-new material paradigm, it can accurately solve the fundamental problems faced by traditional flexible sensors in mechanical compliance, electrical performance limit, and high-density integration through atomic structural characteristics [23]. Firstly, in view of the mechanical mismatch between wearable devices and human tissues, two-dimensional materials such as graphene have extremely low bending stiffness and can fit the micro-nano morphology of skin surface [24]. For example, in the monitoring of epidermal electrophysiological signals, ultra-thin electrodes based on graphene can achieve conformal contact with the skin and improve the monitoring accuracy [25]. Secondly, in order to solve the common problems of insufficient sensitivity and slow response speed of flexible devices, two-dimensional materials provide an adjustable electronic structure, and the bare surface atoms make the carrier transport easily disturbed by the external environment [26], thus realizing ultra-sensitive detection. In the application of wearable sweat biochemical sensing, MoS_2 field effect transistors can monitor the concentration changes of cytokines such as TNF-α in sweat in real time with an extremely low detection limit (femtomolar level) by using their surface sensitivity and combining with an automatic sweat collection and filtration system [27]. Finally, in order to break through the limitation of traditional planar circuits in high-density integration, the van der Waals heterojunction characteristics of two-dimensional materials allow vertical stacking of different functional layers. This vertical integration architecture greatly reduces the device volume, which lays the foundation for building a multi-functional integrated intelligent sensing system [28]. Therefore, two-dimensional materials provide an irreplaceable material science foundation for constructing the next generation of high-performance and multi-modal wearable biosensors.

Here, we summarized the latest development of two-dimensional materials in wearable devices, mainly involving graphene, transition metal disulfides (TMDs), MXenes and Xenes. We first introduced the basic characteristics of these materials, including physical and chemical properties and biocompatibility, and then summarized the related preparation and processing methods for bioelectronics applications. Then, according to the classification of sensing modes (physical/chemical), the working mechanism and performance of transistor-based biosensor devices based on these materials are discussed in detail. On this basis, in order to build a complete intelligent bioelectronic system, we further expound the development status and future challenges of memristor-based artificial synapses at the information processing end and system integration technology covering architecture paradigm, energy supply mechanism and thermal management.

2 The Unique Properties of Two-Dimensional (2D) Materials

With the vigorous development of wearable devices, electronic skin and flexible display, the traditional rigid silicon-based materials encounter bottlenecks in deformation adaptability [29], and the appearance of graphene and various emerging two-dimensional materials just provide unprecedented materials for flexible electronics technology [30]. The application of several main two-dimensional materials in wearable systems is shown in Table 1. People combine these materials with atomic thickness with flexible substrate, which breaks through the limits of traditional sensors in many performances and realizes multi-modal accurate detection from weak physiological signals to ambient gases [31]. The following describes the characteristics of several main two-dimensional materials that have an impact on flexible electronics.

Table 1: Properties and Applications of Common Two-Dimensional Materials in Wearable Electronics.

Material System	Electronic Properties	Core Characteristics	Applications in Wearable Electronics
Graphene	Semimetal (zero bandgap)	Ultra-high carrier mobility (∼15,000 $cm^2/(V·s)$), Young's modulus 1.0 TPa, optical transmittance 97.7%, excellent flexibility	Flexible transparent electrodes (for displays/touch screens), wearable strain/-pressure sensors (motion capture), bioimpedance tattoos (continuous blood pressure monitoring), conductive inks for e-textiles
MXenes (e.g. $Ti_3C_2T_x$)	Metallic conductor	High electrical conductivity (up to 35,000 S/cm), surface hydrophilicity (–OH, –O, –F functional groups), pseudocapacitive properties, high mechanical strength	Flexible micro-supercapacitors (high-wettability energy storage), electrochemical sensors for sweat components, wearable electromagnetic shielding coatings, conductive textiles
TMDs (e.g. MoS_2, WS_2, $MoSe_2$)	Semiconductor (tunable direct bandgap)	Single-layer direct bandgap (MoS_2 ∼1.8 eV), strong spin-orbit coupling, valley polarization effect, X-M-X sandwich structure	High-performance flexible photodetectors (PPG heart rate monitoring, broadband optoelectronic chips), low-power flexible logic circuits, highly sensitive gas sensors
Black Phosphorus (BP)	Narrow-gap semiconductor	Tunable bandgap (0.3–2.0 eV, covering mid-infrared to visible), strong in-plane anisotropy, high carrier mobility, biocompatibility and biodegradability	High-sensitivity infrared body temperature sensors, MXene/BP composite flexible pressure sensors (self-powered systems), transient (biodegradable) wearable electronics
Xenes (e.g. silicene, germanene, antimonene)	Topological/ semiconductor	Buckled honeycomb lattice, sp^2-sp^3 mixed hybridization, strong spin-orbit coupling, tunable topological bandgap, silicon-process compatibility	DNA electrochemical biosensors (silicene), ultra-sensitive miRNA detection via SPR sensors (antimonene), topological quantum flexible devices (frontier exploration)
h-BN	Insulator (wide bandgap)	Wide bandgap (∼6 eV), atomically flat surface free of dangling bonds, high chemical and thermal stability, lattice mismatch with graphene only 1.7%	Gate dielectric layers for flexible transistors, encapsulation/protective layers for sensitive 2D materials (e.g. hBN/BP/hBN), printable dielectric inks, thermal management substrates

2.1 Graphene

At the moment when wearable electronic devices are pursuing all-weather monitoring and human-computer interaction, traditional materials are facing severe challenges: although organic semiconductor materials have certain flexibility, the carrier mobility is low, which seriously restricts the response speed of devices [15]; However, transparent electrodes such as indium tin oxide have excellent conductivity, but it is difficult to bend and stretch repeatedly, and the reliability is low [32].

As a two-dimensional honeycomb lattice structure composed of single-layer carbon atoms, graphene is an ideal transparent electrode material with a light transmittance of 97.7% [18, 33]. The room-temperature carrier mobility can reach 15,000 $cm^2/(V·s)$, far exceeding the traditional semiconductor. Young's modulus is up to 1.0 TPa, and the breaking strength is over 130 GPa [18], so that it can still maintain its structural integrity under extreme bending. The synergistic effect of these properties enables flexible devices based on graphene to achieve unprecedented mechanical stability while maintaining high electrical properties [34].

The conductivity of graphene originates from its unique electronic band structure. In sp^2 hybridization, each carbon atom uses three in-plane sp^2 hybrid orbitals to form strong σ bonds with its neighbors, constructing a rigid honeycomb skeleton that accounts for graphene's exceptional mechanical strength. The remaining out-of-plane p_z orbital on each carbon atom contributes one electron to form delocalized π bonding and π^* antibonding bands. These two bands linearly cross at the K (K') points of the Brillouin zone with zero energy gap, giving rise to a massless Dirac fermion system. The linear energy-momentum dispersion endows charge carriers with pseudospin conservation, which strongly suppresses backscattering, thus achieving ultra-high conductivity and mobility and laying a physical foundation for high-frequency and low-power flexible circuits [35].

Bioimpedance tattoos were prepared by using graphene grown by chemical vapor deposition. By using Young's modulus of 1.0 TPa and ultra-thin characteristics at atomic level,

the electrode was endowed with flexibility and skin conformal ability, which enabled the device to maintain stable contact with the skin when it experienced repeated bending and stretching caused by human daily activities, and avoided signal noise caused by interface slippage. At the same time, thanks to its high carrier mobility of 15,000 $cm^2/(V \cdot s)$ at room temperature, the system realizes the acquisition of bio-impedance signals with extremely low noise. The experimental data show that the device can always keep the diastolic blood pressure measurement accuracy within 4.5 mmHg during the continuous 300-minute dynamic monitoring process, and solve the problems of signal attenuation and mechanical failure of traditional materials in physiological monitoring [36]. At the same time, the chemical stability and biocompatibility of graphene ensure the safe operation of equipment in complex environment [37].

Although graphene is excellent in electrical conductivity and mechanical flexibility, its application in wearable electronics still faces two major bottlenecks. Firstly, although the zero band gap characteristic endows it with extremely high carrier mobility, the on-off ratio of graphene field effect transistor is extremely low, which limits its application in biosensor logic circuits. Secondly, due to the lack of biospecific recognition, the inert surface of graphene lacks active sites that specifically bind with biomolecules, and surface functionalization is needed to detect specific physiological markers, which increases the process complexity of device preparation.

2.2 MXenes

At present, wearable electronic devices are rapidly evolving toward multifunctional integration and miniaturization, placing increasingly stringent demands on internal micro-energy storage units [11]. Conventional carbon-based electrodes suffer from inherent hydrophobicity, which impedes complete electrolyte infiltration and reduces the effective electrode/electrolyte contact area. This not only limits ion transport efficiency but also induces interfacial debonding under mechanical deformation, compromising the reliability of flexible electronics.

MXenes, a family of two-dimensional transition metal carbides, nitrides, and carbonitrides with the general formula $M_{n+1}X_nT_x$ [12], provide a promising solution to these limitations. Their surface terminations (–OH, –O, –F) endow MXenes with strong hydrophilicity [38], enabling atomic-level contact with aqueous electrolytes and maximizing the utilization of electrochemically active sites. Meanwhile, MXenes exhibit metallic conductivity up to 35,000 $S\,cm^{-1}$ and outstanding mechanical strength, with macroscopic MXene fibers reaching a tensile strength as high as 958 MPa [39]. This combination ensures efficient electron transport and structural integrity under complex deformations, satisfying the dual requirements of high wettability and high electrical conductivity for flexible energy storage devices.

To understand the origin of this high conductivity, one must consider the evolution of the electronic structure during synthesis. In the MAX phase, the transition metal layers and element A are tightly bound by strong chemical bonds, restricting electron mobility. Upon selective etching of the A layer, the electronic structure of the transition metal carbides is reorganized: the electronic states originally occupied by element A disappear, leading to a marked increase in the density of states of the metal d orbitals. In particular, the p orbitals of surface terminations hybridize with the d orbitals of transition metals, effectively modulating the Fermi level and preserving the metallic conductivity of MXenes [40]. This electronic configuration enables nearly unimpeded in-plane electron transport, allowing MXenes to retain both hydrophilicity and metallic conductivity at the atomic scale.

This unique combination of properties is exemplified in flexible MXene-based micro-supercapacitors fabricated via liquid-crystal self-assembly. Benefiting from the intrinsic hydrophilicity of MXenes, mechanical shearing induces the vertical alignment of discotic liquid crystals, and free-standing films are constructed using supercritical drying. Even at thicknesses up to 200 μm, the devices exhibit extremely low ion transport resistance and support rapid charge–discharge cycling. Under repeated mechanical bending, the continuous vertical conductive network and stable electrode/electrolyte interface suppress mechanical fatigue and maintain excellent electrochemical performance, demonstrating the key role of MXenes in reconciling wettability and conductivity for flexible electronics [41].

Despite these advantages, the practical application of MXenes remains constrained by environmental stability and synthesis complexity. Most MXenes are susceptible to oxidative degradation in oxygen-rich aqueous environments or humid air, leading to surface reconstruction and electrochemical performance decay, which presents a considerable challenge for long-term wearable devices. In addition, current synthesis routes typically rely on aggressive fluoride-based etchants (e.g., HF or Lewis acids), raising environmental and safety concerns. Residual etchants that are difficult to remove completely may also pose cytotoxicity risks, limiting the direct use of MXenes in bioelectronic devices that require intimate tissue contact.

2.3 TMDs

Single-layer TMDs are two-dimensional materials with the general formula of MX_2 (M is a transition metal such as Mo and W, and X is a chalcogenide element such as S and Se). Its single-layer structure presents a unique "sandwich" configuration (X-M-X) [19, 20], which not only endows the material with atomic thickness and excellent mechanical flexibility [42], but also leads to a fundamental change in the electronic structure: when the material is thinned to a single layer, the band gap transforms from indirect to direct [43]. This characteristic makes TMDs possess both excellent switching characteristics of semiconductors and strong light-matter interaction, and the band gap covers from visible light to near-infrared band [44], which fills the gap in photoelectric conversion between graphene and MXenes.

The physical mechanism of the direct band gap formation requires attention to the electronic band reconstruction at atomic-layer thickness. In multilayer TMDs, there is strong interlayer coupling between the electronic states derived from the d orbitals of the metal atoms and the p orbitals of the chalcogenide elements. This coupling pushes the conduction

band minimum near the Γ point downward and raises the valence band maximum, making the global band extrema located at different k-points and thus forming an indirect band gap. However, when the material is exfoliated to a single layer, the interlayer coupling vanishes. Take MoS_2 as an example: in the monolayer structure, the states near the Γ point that were strongly affected by interlayer interaction shift away from the band edges, while the d orbitals of molybdenum atoms and the p orbitals of sulfur atoms form both the conduction band minimum and valence band maximum at the K (K') points of the Brillouin zone [45]. Since both band extrema are now located at the same k-point, electronic transitions can be achieved directly through photon excitation without the assistance of phonon momentum exchange. Meanwhile, the broken spatial inversion symmetry in monolayer TMDs (point group D_{3h}) lifts the spin degeneracy at K and K' valleys through spin-orbit coupling, giving rise to spin-valley locking—a property that opens new possibilities for valleytronic devices. This indirect-to-direct band gap transition driven by the elimination of interlayer coupling through quantum confinement provides an efficient radiative recombination channel for two-dimensional optoelectronics.

This characteristic shows great application potential in high-performance photodetectors. By nitrogen plasma doping, a lateral homojunction is constructed in MoS_2, which not only preserves the high-mobility transport channel at the bottom, but also realizes efficient separation of photo-generated carriers. Under 638 nm illumination and −27 V gate voltage, the optical switch ratio of the device reaches as high as 10^7, and the photoresponsivity reaches 6.94×10^4 A W^{-1}. It is worth noting that the impurity energy band introduced by nitrogen doping extends the response range of the device to short-wave infrared, and still shows 34 A W^{-1} responsivity in this band, which provides a new strategy for realizing silicon-based compatible wide-spectrum optoelectronic integrated chips [46].

Although single-layer TMDs have excellent photoelectric properties, they face the dual challenges of large-scale preparation and thermal management in flexible device integration. On the one hand, it is extremely difficult to grow high-quality monolayer films over a large area. At present, when preparing large-area uniform single-layer TMDs by CVD method, it is often accompanied by grain boundary defects and uneven layers, which leads to large dispersion of device array performance. On the other hand, the extremely low thermal conductivity of TMDs (compared with graphene) makes them face serious heat dissipation problems when operating at high power density. In the wearable scene that closely fits human skin, if the power consumption of the device is slightly higher, the accumulated heat will not only reduce the life of the device, but also cause thermal damage to the wearer's skin.

2.4 Black Phosphorus

Although TMDs have achieved a direct band gap transition from visible to near-infrared in a single layer, their band gap coverage is still concentrated in the visible-near-infrared range, and it is difficult to extend the response to the mid-infrared region (wavelength 3–8 μm). In wearable health monitoring, real-time perception of human radiation temperature (thermal radiation peak at about 9.5 μm) is important for early warning of inflammation, fever and circadian rhythm analysis. However, TMDs can not satisfy the demand. In addition, the growing global electronic waste crisis has prompted the development of transient electronics that can degrade on their own and disappear after the end of their service life [47]. Black phosphorus (BP), a two-dimensional layered semiconductor with a puckered orthorhombic lattice structure (D_{2h} point group) [48], fills this gap precisely. Its band gap varies continuously from approximately 0.3 eV in bulk to approximately 2.0 eV in monolayer [49], covering the electromagnetic spectrum from mid-infrared to visible light, which is a complementary band gap window that neither graphene nor TMDs can provide. At the same time, BP has natural biocompatibility and can be degraded into non-toxic phosphate in vivo [50], providing a material basis for transient wearable electronics.

The physical origin of the continuously tunable band gap of BP is rooted in the layer-dependent quantum confinement effect. In the multilayer structure, the coupling between layers leads to the delocalization of the wave function in the direction perpendicular to the plane, the conduction band bottom and the valence band top converge at the Γ point in the Brillouin zone, and the band gap is narrowed to approximately 0.3 eV. When the number of layers is gradually reduced to a single layer, the interlayer coupling disappears, the quantum confinement in the perpendicular direction is significantly enhanced, the spatial distribution of the wave function is strictly limited to a single atomic layer, and the energy level splitting increases, resulting in the band gap widening to approximately 2.0 eV [49]. Unlike the band structure reconstruction caused by the elimination of interlayer coupling in TMDs, BP always maintains its direct band gap nature at the Γ point regardless of the number of layers, which provides an efficient radiation recombination channel over the entire thickness range. It is worth noting that the puckered lattice structure of BP leads to huge differences in the effective mass of carriers along the armchair and zigzag directions. The effective mass of carriers along the zigzag direction is approximately 10 times that of the armchair direction [51], which results in the room-temperature carrier mobility along the armchair direction being as high as 300–1000 $cm^2/(V{\cdot}s)$, while the zigzag direction is only 50–120 $cm^2/(V{\cdot}s)$ [52]. This strong in-plane anisotropy not only provides a new dimension for the design of direction-selective electronic and optical devices, but also makes it a unique platform for exploring anisotropic physics.

This combination of tunable narrow band gap and mechanical flexibility has been verified in self-powered wearable sensing systems. By using layer-by-layer self-assembly technology, a periodic interleaving MXene/BP lamellar thin film was constructed to simultaneously realize two functions: flexible pressure sensing and energy storage. In the pressure sensing module, the BP component introduces a high-density carrier transport channel, and cooperates with the metal conductivity of MXene to form a synergistic conductive network, which makes the pressure sensitivity of the device reach 77.61 kPa^{-1} with an optimized elastic modulus of 0.45 MPa.

In the energy storage module, the interleaving lamellar structure provides abundant ion transport paths for the direct-laser-writing micro-supercapacitor, which can efficiently store the energy collected by the integrated solar cell and compensate the intermittency of light illumination. The integrated system shows a fast response time of 10.9 ms and is capable of real-time detection of the beating of the human heart under physiological conditions [53]. This work demonstrates that BP can not only serve as an active sensing unit, but also be deeply coupled with other two-dimensional materials to build a self-sustaining wearable platform.

Although black phosphorus has remarkable advantages in band gap tunability and anisotropic transport, its practical application still faces two core challenges. Firstly, environmental instability is the most prominent bottleneck. BP is extremely prone to oxidative degradation in ambient atmosphere containing oxygen and moisture [54], which leads to the reconstruction of the surface lattice and the sharp attenuation of electrical properties. The few-layer BP transferred out of the growth environment can undergo significant degradation within hours to days without encapsulation. This characteristic forces the device preparation and integration process to rely on inert atmosphere protection or additional encapsulation layers (such as h-BN), which increases the process complexity and cost. Secondly, the large-area controllable preparation of high-quality few-layer BP thin films remains a technical challenge. The current mainstream methods, whether mechanical exfoliation or liquid phase exfoliation, are difficult to achieve uniform films with controllable layers in a large area, which limits the batch consistency and yield of device arrays.

2.5 Xenes

During the evolution of flexible electronics technology toward quantum devices beyond Moore's Law, a core challenge is how to induce topological electronic states in two-dimensional materials lacking natural band gaps. Xenes provide a unique solution to this problem. Among them, group IV Xenes such as silicene and germanene are highly consistent with the core elements of the bulk semiconductor industry, and are expected to inherit the mature silicon-based process foundation. At the same time, the unique buckled honeycomb lattice induces mixed sp^2–sp^3 hybridization and strong spin-orbit coupling (SOC) effects [55], which makes it possible to open topologically nontrivial band gaps in zero-band-gap materials, thus laying a material foundation for building new electronic devices with high-speed transmission and quantum control capabilities on flexible substrates.

Xenes materials show unique advantages in the fields of flexible bioelectronics and next-generation wearable devices. Thanks to their ultra-thin two-dimensional structure and excellent photoelectric characteristics, Xenes have been explored for developing high-performance flexible sensors. The DNA electrochemical biosensor based on silicene can specifically recognize the complementary strand of single-stranded DNA. As an integrated circuit biosensor, it can be used to manufacture lab-on-chip devices for DNA sequencing [56]; The surface plasmon resonance sensor based on antimonene has a detection limit of about 10 aM, which is used to detect microRNA, an important biomarker for cancer diagnosis. Compared with the traditional quantitative technology of miRNA, the clinical-related SPR real-time detection (POC) platform based on antimony material has significantly improved the detection efficiency [57].

Although Xenes have subversive potential in theory, their practical application is still in the primary stage, mainly limited by harsh preparation conditions and environmental instability. Unlike graphene or TMDs, most Xenes are prone to chemical adsorption or oxidation in ambient environment [58]. For example, silicene can only exist stably in air for several minutes, so its transfer from the growth substrate to a flexible substrate requires an ultra-high vacuum environment.

2.6 h-BN

The previous sections describe two-dimensional materials that serve as active functional elements in wearable devices, from the conductive electrodes of graphene, the energy storage units of MXenes, the photoelectric conversion channels of TMDs, the infrared sensing layers of black phosphorus, to the topological quantum channels of Xenes. However, a complete flexible electronic system also requires an indispensable class of passive support materials: high-quality dielectric layers that provide electrostatic gate control and encapsulation layers that isolate the active materials from the external environment. When traditional dielectric materials such as SiO_2 and Al_2O_3 are deposited on two-dimensional semiconductors, a large number of dangling bonds and charge traps will be generated at the interface due to the lattice mismatch and the lack of chemical bonds at the van der Waals surface [59]. These defect states will cause serious hysteresis in the transfer characteristic curve of the transistor, reduce the carrier mobility, and severely limit the reliability of flexible circuits. At the same time, as mentioned above, environmentally sensitive materials such as black phosphorus and Xenes are extremely susceptible to oxidative degradation in ambient atmosphere, and urgently need an atomic-level dense encapsulation barrier. Hexagonal boron nitride (h-BN), known as "white graphene", provides an ideal solution for both problems.

h-BN has a layered honeycomb lattice structure very similar to graphene, with boron and nitrogen atoms alternating at the sublattice positions. However, unlike the electron delocalization in graphene, the strong electronegativity difference between B and N atoms leads to the extreme localization of π electrons on the nitrogen sublattice sites [60]. This localization mechanism fundamentally changes the electronic structure: the degeneracy of π and π^* orbitals at the Dirac point is broken, opening a wide band gap of approximately 5.9–6.1 eV [61], which makes h-BN an excellent insulator. More critically, the surface of h-BN is atomically flat, almost free of dangling bonds and charge trap states. When it is used as a substrate or dielectric layer for two-dimensional semiconductors, it can form a clean van der Waals interface, which greatly suppresses carrier scattering and hysteresis. In addition, h-BN has a lattice mismatch of only 1.7% with graphene [62], making it the natural substrate material for constructing high-quality van der Waals heterostructures. Its thermal conductivity can reach up to 8.1 W/(m·K) in the

cross-plane direction for submicrometer-thick flakes [63], combined with excellent chemical stability, which provides a thermal management solution for flexible electronic devices.

The synergy of these properties has been demonstrated in fully two-dimensional flexible transparent transistors. By using MoS_2 as the channel, h-BN as the gate dielectric, and graphene as the gate electrode, a van der Waals heterostructure field-effect transistor was constructed entirely from two-dimensional materials [64]. The device shows a field-effect mobility of up to 45 $cm^2/(V{\cdot}s)$, with greatly reduced hysteresis, and an operating gate voltage below 10 V. When integrated onto a flexible polymer substrate, the device maintains unchanged electrical performance up to 1.5% strain. The key contribution of h-BN is that its atomically flat and dangling-bond-free surface provides a clean dielectric interface that eliminates the charge traps inherent to conventional oxide dielectrics. Furthermore, h-BN encapsulation has been proven to be an effective strategy for protecting environmentally sensitive materials. In the hBN/BP/hBN sandwich structure, h-BN completely isolates black phosphorus from oxygen and water molecules at the atomic level, enabling BP photodetectors to achieve stable mid-infrared response at room temperature while effectively preventing oxidative degradation [65]. This encapsulation strategy has been widely adopted in the integration of various air-sensitive two-dimensional materials.

Although h-BN shows irreplaceable advantages in dielectric and encapsulation functions, it still faces application challenges. Firstly, as a layered material, h-BN is usually obtained by mechanical exfoliation or synthesized at high temperature, and it is difficult to achieve reliable large-area deposition as a top-gate dielectric [59]. The critical film thickness effect is particularly noteworthy: when the h-BN film exceeds a critical thickness of approximately 10 nm, its breakdown electric field strength and leakage current mechanism change significantly, indicating that the electrical properties are closely related to the growth mode and film quality [66]. Secondly, the relatively low dielectric constant of h-BN ($\varepsilon_r \approx$ 3–4) means that larger gate voltages are required to achieve the same charge induction capability compared to high-κ dielectrics such as HfO_2, which limits its application in ultra-low-power flexible circuits. Nevertheless, as the only widely recognized two-dimensional insulator, h-BN plays an irreplaceable role as the "behind-the-scenes enabler" of the entire two-dimensional materials ecosystem—providing high-quality interfaces and environmental protection for all the active materials discussed above, and ensuring the long-term reliable operation of wearable devices in complex human body environments.

3 Intelligent Sensing Interface

Two-Dimensional (2D) materials, leveraging their atomic-scale thickness, tunable band structures, exceptional flexibility, and engineered interfacial properties, offer unprecedented pathways for multimodal intelligent functionalities in wearable systems. These characteristics not only enable breakthroughs in sensitivity perception, soft actuation, signal processing, and energy management but—more critically—facilitate on-device signal amplification, filtering, and pattern recognition through the deep integration of intrinsic material properties and structural design. This establishes a new paradigm of "material-as-computation" platforms that are low-power, highly integrated, and progressively permeating all modules of the "sensing–processing–energy–communication" closed-loop system through heterogeneous integration.

3.1 Biochemical Sensing: Paradigm Shift in Sweat Biomarker Detection

Human sweat serves as an ideal non-invasive window for health monitoring, containing critical metabolic biomarkers such as glucose, lactate, and electrolytes. With the escalating global prevalence of diabetes, the development of non-invasive, real-time, and reliable continuous glucose monitoring (CGM) systems has become an urgent imperative [67]. Although wearable electrochemical biosensors represent the mainstream technological approach for sweat glucose detection, their advancement has long been constrained by three fundamental challenges. In enzymatic detection systems, the catalytic reaction of glucose oxidase (GO_x) is highly dependent on dissolved oxygen. Conventional patch-type sensors pressed against the skin induce oxygen deficiency in sweat (typically <50 μM), compressing the linear detection range (<5 mM) and degrading sensitivity (typical value <5 $\mu A \cdot mM^{-1} \cdot cm^{-2}$). Simultaneously, the enzyme protein is susceptible to temperature, humidity, and pH fluctuations, resulting in poor long-term stability (half-life <7 days) [68]. In non-enzymatic systems, electrocatalytic electrodes face multiple bottlenecks: severe interference from coexisting reductants such as ascorbic acid and uric acid (selectivity coefficient <3); insufficient intrinsic activity of single-metal catalytic sites (e.g., Ni, Cu) leading to low sensitivity (<10 $\mu A \cdot mM^{-1} \cdot cm^{-2}$); agglomeration and detachment of nanocatalysts (e.g., Pt) during dynamic use (cyclic stability $<1{,}000$ cycles); and critically, the inability of traditional rigid electrodes (carbon rods, metal wires) to accommodate skin deformation, causing dynamic detection failure and biocompatibility issues.

3.1.1 Construction of Solid-Liquid-Gas Triphase Interfaces and Performance Enhancement in Enzymatic Sensors

In enzymatic glucose detection, the catalytic reaction of glucose oxidase heavily relies on dissolved oxygen. In traditional wearable patches for detecting biomarkers in sweat, the sensor is closely attached to the skin, leading to insufficient oxygen in sweat. This affects the sensitivity of enzymatic sensors, thereby limiting their linear detection range and sensitivity. Additionally, enzyme materials are prone to degradation, which impacts the reusability of the sensor. Moreover, traditional fabrication techniques such as screen printing and electrodeposition result in short sensor lifespan and poor stability. To address this challenge, researchers developed an innovative sensor structure in 2019 using a $Ti_3C_2T_x$ and Prussian Blue composite material, successfully constructing an efficient "solid-liquid-gas" three-phase interface [69]. The principle is shown in Figure 1, this design utilizes the layered stacking structure of MXene nanosheets as a highly conductive framework, effectively preventing the agglomeration of

Prussian Blue nanoparticles—an excellent artificial peroxidase—while its porous structure promotes oxygen diffusion and exchange. The composite sensor demonstrated remarkable performance in sweat glucose detection, with a sensitivity as high as 35.3 $\mu A \cdot mM^{-1} \cdot cm^{-2}$, enabling it to capture glucose fluctuations even at extremely low concentrations. At the same time, the synergistic effect at the solid-liquid-gas interface resolved the "oxygen deficit" issue, ensuring a linear response even at high glucose concentrations. For lactate detection, the system also exhibited excellent performance, achieving a sensitivity of 11.4 $\mu A \cdot mM^{-1} \cdot cm^{-2}$, thereby improving detection performance and stability.

In such enzymatic sensors, the high surface area of two-dimensional materials provides a larger carrier for glucose oxidase, enhancing the efficiency of direct electron transfer. This contributes to improved sensitivity, greater selectivity, and further miniaturization of wearable biochemical sensors.

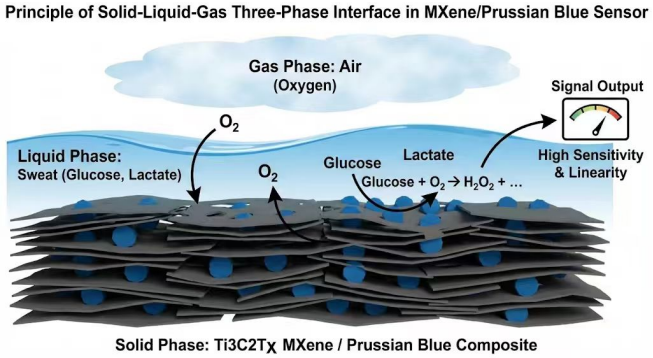

Figure 1: Schematic illustration of the $Ti_3C_2T_x$/Prussian Blue composite-based solid-liquid-gas triphase enzymatic sensor for sweat glucose and lactate detection.

3.1.2 Liquid Metal-Enhanced Non-Enzymatic Sensing: An Emerging Paradigm

The integration of two-dimensional (2D) materials with metallic counterparts holds significant promise for non-enzymatic wearable flexible sensors. Such sensors circumvent the inherent limitations of conventional enzymatic systems, such as enzyme instability and poor longevity, thereby offering a robust solution for sustained and reliable biomolecular monitoring. A 2025 study published in *iScience* exemplifies this potential, where the synergistic combination of 2D material architecture and metallic properties enabled the development of a highly sensitive, flexible, and sweat-inducing non-enzymatic electrochemical wearable sensor for real-time dynamic monitoring of glucose in sweat [70]. The principle is shown in Figure 2, this work innovatively employed a composite of liquid metal gallium (Ga) and the 2D transition metal carbide/nitride (MXene), integrated with chitosan (CS) hydrogel to form a Ga@MXene/CS three-dimensional porous conductive hydrogel network. Specifically, the high fluidity and intrinsic conductivity of liquid Ga effectively address the mechanical fragility of traditional flexible conductive materials under repeated deformation, while MXene, as a representative 2D material, contributes its layered structure with high surface area and excellent electrocatalytic activity. Their synergy not only overcomes the mechanical limitations of conventional sensors (e.g., poor bendability or stretchability) but also establishes a stable three-dimensional porous architecture through Ga intercalation within MXene interlayers. This design substantially enlarges the electrode-electrolyte reaction interface, mitigating the sensitivity constraints imposed by the flat surfaces of conventional electrodes. Concurrently, the formation of Ga–O–Ti chemical bonds between Ga and MXene reinforces structural stability in the complex sweat environment, suppressing aggregation and detachment while enhancing dispersion uniformity and interfacial adhesion strength. The incorporation of chitosan further optimizes system performance: its hydrophilic network ensures prolonged water retention, and its natural bioadhesive properties guarantee secure skin contact, minimizing signal drift during motion. Critically, leveraging its superior conductivity and biocompatibility, the device can also function as an electrode for iontophoresis therapy, actively inducing localized sweating via low-intensity current to achieve "on-demand detection", thereby eliminating reliance on exercise-dependent perspiration. This advancement not only underscores the pivotal role of 2D material-metal composites in enhancing sensor performance but also lays a crucial foundation for developing non-invasive, intelligent wearable health monitoring platforms. Related design principles are gaining broad traction in recent flexible electronics research; for example, the application of graphene/liquid metal composites in lactate sensing further validates the generality of such architectures.

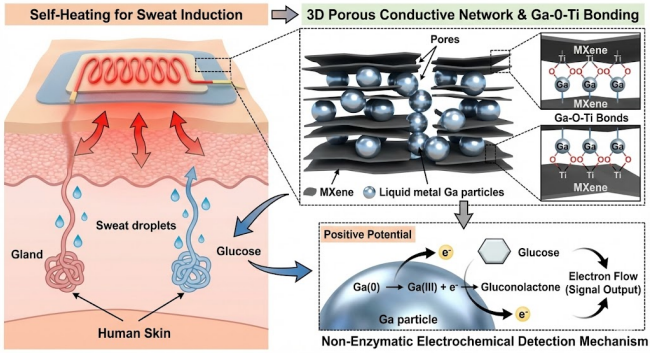

Figure 2: Schematic Illustration of Self-Heating, Non-Enzymatic Sweat Glucose Sensing Mechanism Based on 3D Porous MXene/Ga Composite.

Furthermore, significant progress has also been made in non-enzymatic sensors based on Pt/MXene (platinum nanoparticle-decorated MXene). Research demonstrates that by immobilizing the Pt/MXene catalyst within a conductive hydrogel, the impact of mechanical deformation on the catalytic interface can be effectively mitigated. This enables continuous monitoring of glucose in sweat over a broad linear range of 0–8 mM, while maintaining a high sensitivity of 48 $\mu A \cdot mM^{-1} \cdot cm^{-2}$ [71].

These sensors not only incorporate two-dimensional materials for material innovation, but also enhance non-enzymatic flexible sensors by integrating three distinct types of materials through well-engineered architectures. This approach provides a scalable and general design strategy for applying 2D materials in flexible electronic sensing devices. Currently, the most mature and reliable pathway for wearable glucose detection, both domestically and internationally, is

a composite strategy that combines minimally invasive sampling, electrochemical detection, non-enzymatic design, and two-dimensional materials. This integrated approach enables both signal stability and high sensitivity [72].

3.2 Physical and Mechanical Sensing

Beyond sweat-based biochemical sensing in wearable technology, physical signal monitoring represented by electronic skin (E-skin) constitutes another major sector of the field. The core functions of E-skin include capturing physical signals such as pulse, blood pressure, and limb movement. A key challenge in this area lies in achieving high sensitivity while maintaining wide-range stretchability and good breathability. Early E-skin systems provided only basic tactile sensing, typically employing silicon-based pressure sensors, metal electrodes, conventional wires, and rigid circuit boards, resulting in bulky hardware with limited functionality. The subsequent introduction of flexible substrates such as polyimide improved device bendability, yet failed to offer sufficient stretchability, thus restricting their use in dynamic motion monitoring. The emergence of two-dimensional (2D) materials has brought revolutionary progress to E-skin development. By combining the intrinsic properties of 2D materials with ingeniously designed microstructures, it is now possible to simultaneously achieve both high sensitivity and high stretchability—attributes that were previously difficult to realize in conventional E-skin systems [73].

Two-dimensional materials generally exhibit excellent mechanical strength and high toughness. The van der Waals interactions between adjacent layers allow for interlayer shear and sliding, providing the material with favorable deformation adaptability [74]. Compared to traditional three-dimensional materials, 2D materials can withstand greater mechanical strain before failure [75]. Furthermore, they possess superior electrical properties such as tunable bandgaps and high carrier mobility. Coupled with their compatibility with large-area processing techniques, these characteristics make 2D materials highly promising for developing powerful yet cost-effective wearable devices [76].

The electromechanical coupling characteristics of sensors based on two-dimensional materials exhibit distinct behaviors at microscopic and macroscopic scales. At the micro scale, minor stress and strain can directly alter the electrical and optical properties of atomic layers by modifying the atomic lattice and electronic band structure. On the macro scale, the electromechanical coupling behavior of sensors is influenced not only by the crystallographic properties of the material, but also by multidimensional factors such as substrate interactions, shape, and dimensions [77].

Yang et al. fabricated a piezoresistive sensor for acoustic signal detection using functionalized graphene multilayers [78]. Liu et al. developed a nonlinear wearable sensor based on the piezoresistive effect, composed of hydrophobic polyimide nanofibers and MXene composite aerogel, for detecting human motion and physical signals [79]. Zheng et al. integrated MXene with cotton fabric to create a flexible, intelligent electronic skin capable of sensing physiological signals through pressure [80]. Chao et al. engineered a higher-performance electronic skin using MXene and protein nanocomposites via the piezoresistive effect, which demonstrated durability over 10,000 usage cycles [81]. In the emerging field of bio-inspired robotics, Choi et al. fabricated a linear, piezoelectric pressure sensor based on large-area sputtered asymmetric two-dimensional MoS_2 [82].

In addition to the intrinsic properties of materials, structural design can also enhance sensitivity. For example, the application of Kirigami-structured graphene in electronic skin demonstrates this principle. Although graphene exhibits an extremely high Young's modulus, its intrinsic ductility is very poor (<3%), which limits its application in monitoring large deformations at joints. Inspired by the traditional art of Kirigami, researchers have successfully overcome the trade-off between sensitivity and stretchability by designing specific micro/nano-cutting patterns on graphene oxide (GO) or laser-induced graphene (LIG) films. The Kirigami structure converts macroscopic stretching of the material into local bending and twisting of the microstructures, thereby avoiding brittle fracture of the conductive pathways. A 2024 review noted that the introduction of Kirigami structures can increase the maximum stretchable strain of graphene-based sensors to over 79% while maintaining the integrity of the conductive network [83]. The "FlexiPulse" sensor based on a vertical Kirigami structure, developed by Meng et al., demonstrates extremely high pressure sensitivity, enabling precise capture of subtle features in radial artery pulse waves (such as the dicrotic notch). The device can not only monitor heart rate in real-time but also derive deeper cardiovascular parameters, such as the arterial stiffness index, through waveform analysis [84].

Overall, two-dimensional materials are progressively permeating every module of the closed-loop "sensing–processing–energy–communication" system. Through heterogeneous integration and structural design, they are enabling the development of wearable platforms that exhibit intelligence at the material level.

4 Core Functional Device

4.1 Sensing Device: Transistor-based Biosensor

Transistor-based biosensor is a kind of flexible electronics detection device based on field effect transistor (FET) architecture. The core mechanism is that the biochemical reaction signal is directly converted into an amplified electrical signal by using the interaction between the semiconductor channel layer and the biological analyte (such as charge transfer or doping effect) [85]. Such devices have great potential in many fields, such as medical diagnosis [86], environmental monitoring and food safety [87, 88], and have become an important research direction in the field of wearable electronics. However, although this technology shows great application potential, traditional flexible transistors still face severe performance bottlenecks. The first challenge stems from the inherent contradiction between mechanical flexibility and electrical properties. In order to achieve the characteristics of bending or stretching, devices usually need to be built on

low-modulus polymer substrates or flexible organic semiconductor materials, but this often leads to a significant decrease in carrier mobility [15].

Two-dimensional materials have attracted much attention in the research of transistor-based biosensors because of their atomic thickness, large surface area and high active site density. Graphene has a unique hexagonal lattice structure. In the field effect transistor sensor architecture, its conductivity shows extremely high sensitivity to the change of interface charge caused by the adsorption of external biomolecules, and it can realize ultra-sensitive detection of biomarkers such as SARS-CoV-2 (LOD as low as fg/mL) [89]. Wang et al. successfully realized the ultra-sensitive detection of thrombin by using the photoelectrochemical transistor constructed by graphene channel and introducing metal-organic framework as photosensitive gate. In this study, graphene channel can respond to the weak ion doping effect caused by photovoltaic voltage because of its excellent carrier mobility and extreme sensitivity to interface potential, thus producing a significant bipolar current switching response. The graphene-based sensor achieves a detection limit as low as 0.1 fM [90]. This data proves that, unlike traditional flexible transistors which are limited by bulk material characteristics and low interfacial coupling efficiency, graphene materials can achieve signal transduction through a full-surface conduction mechanism with high efficiency. However, limited by the current wet transfer preparation process, it faces the challenges of interface pollution and structural defects in large-scale preparation, which leads to the device being inferior to the traditional bulk semiconductor materials in stability and repeatability [91].

Transition metal chalcogenides not only have the advantage of surface dominant conductivity, but also have semiconductor characteristics and suitable band gap. This energy band structure determined by atomic arrangement enables TMDs to achieve a high current on-off ratio while maintaining high surface activity [92], thus providing an optimized path at the structural level to solve the performance stability problem of flexible transistors in dynamic monitoring. This characteristic has been verified in the flexible photoelectric biosensor developed by Chen et al. The research shows that the photo-generated carriers can be effectively excited by irradiating the single-layer MoS_2 channel with red light, thus significantly enhancing the output current and signal-to-noise ratio of the device. This photoelectric cooperative strategy not only makes use of the light response characteristics of MoS_2, but also overcomes the severe challenge faced by traditional field effect transistor biosensor in high ion intensity environment—the sharp decline of sensitivity caused by the shielding effect of electric double layer. Experimental data show that the sensor still maintains high specificity and low detection limit (7.57 ng/mL) for human immunoglobulin G in complex matrix. However, although the device has the potential of anti-interference in the energy band structure at the atomic level, in the actual detection process, in order to alleviate the shielding of interface charges in high-salt environment and restore the detection sensitivity, it still has to rely on phosphate buffer for repeated cleaning to reduce the interface ion strength, which shows that the current biosensor based on TMDs cannot realize label-free and continuous in-situ detection [93].

Two-dimensional materials, with their completely exposed surface atoms and rich active sites, show advantages that traditional bulk materials cannot match in surface chemical regulation. Taking advantage of this feature, researchers are no longer limited to MOSFET structures isolated by insulating dielectric layers, but develop an innovative structure without dielectric layers: stable two-dimensional semiconductors such as molybdenum disulfide are directly used as conductive channels, and the sensing process is driven by the direct interaction between surface active sites and analytes. Based on this mechanism, the researchers successfully constructed a competitive hybridization detection strategy by taking advantage of the specific affinity of molybdenum disulfide for single-stranded DNA over double-stranded DNA, thus realizing highly sensitive identification of the target gene sequence on the electrochemical sensing platform. Lee et al. constructed a label-free immunosensor based on multi-layer MoS_2 field-effect transistors, and realized highly sensitive detection of PSA by directly physically adsorbing anti-PSA antibodies, with a detection limit of 1 pg/mL, which is three orders of magnitude higher than the clinical diagnosis threshold [94].

4.2 Computing Device: Memristor-based Artificial Synapse

The latest research progress of transistor-based biosensor is systematically summarized in the previous part. As the core sensing unit of bioelectronic system, it has successfully achieved accurate capture and conversion of physical and chemical signals in vivo. However, the massive raw signals output by sensing devices still need to be processed efficiently before they can be transformed into characteristic information with decision-making value. This demand has promoted the rapid development of information processing systems, among which memristor-based artificial synapses, which can simulate the plasticity of biological synapses, have become the core research direction of information processing systems in the field of bioelectronics because of their brain-like computing advantages of low power consumption and high parallelism. The following will focus on the development status and technical breakthrough of this kind of information processing system.

The unique physical and chemical properties of two-dimensional materials represented by MoS_2 provide a key path for the performance optimization of memristor-based artificial synapses. From the perspective of atomic structure, MoS_2 has a strict sandwich layered structure (S-Mo-S), in which the layers are closely bonded by strong covalent bonds, while the layers are stacked by weak van der Waals force. This feature enables the material to be stripped to the atomic thickness [92], thus strictly limiting the ion migration and resistance change process in the two-dimensional plane. Compared with bulk materials, the surface of MoS_2 has no dangling bonds, which effectively inhibits the disorderly growth of conductive filaments, makes the evolution of conductance state more controllable, significantly improves the

uniformity and stability of synaptic devices, and creates physical conditions for the realization of highly reliable artificial synaptic arrays [95]. Fa et al. constructed artificial synaptic devices with excellent performance by using wafer-level MoS_2 grown by metal organic chemical vapor deposition. The van der Waals gap of MoS_2 plays a key role in atomic confinement, which strictly limits the migration of silver ions and filament growth in the two-dimensional plane. This mechanism fundamentally changes the evolution mode of filaments: experimental observations confirm that filaments show controllable lateral growth between MoS_2 layers, rather than random penetrating growth in the traditional bulk phase. The advantage of this mechanism translates into significant performance improvement. MoS_2-based devices show excellent uniformity and robustness. 100 devices were randomly tested on the wafer scale, and 98 of them showed stable intermediate resistance switching behavior, achieving a device yield of up to 98%. In addition, the device also has the characteristics of low power consumption, long retention and the ability to simulate the plasticity of biological synapses on the microsecond scale, which proves that MoS_2 successfully transforms the resistance mechanism of memristors from random noise to controllable physical process through its unique layered confinement effect [96].

Although traditional two-dimensional semiconductor materials, such as MoS_2, perform well in electronic devices, single-material memristors are often limited by the inherent carrier transport mechanism, and it is difficult to achieve efficient leakage current suppression in the dark state and polar photocurrent response under illumination at the same time, resulting in low coupling degree of devices in light sensing and computing functions [97]. To solve this problem, MXene plays an obvious role as a functional modulation layer. With its unique layered structure and rich surface functional groups, MXene plays an interface role in MXene/$CuInS_2$ heterojunction, and reconstructs the transport path of carriers through the interface dipole effect: in the dark state, MXene raises the valence band top of $CuInS_2$ and increases the hole injection barrier, thus effectively suppressing the leakage current; under illumination, MXene promotes the spatial separation of electron-hole pairs, realizes the cooperative transmission of electrons and holes, and even induces the reversal of photocurrent response. The innovation of this mechanism directly solves the pain points of traditional single material memristor, such as non-polarity reversal of photocurrent and large dark current noise. The photoelectric synapse device based on MXene not only achieves a switching ratio as high as 10^2, but also simulates the plasticity of biological synapses [98]. This proves that MXene can not only reduce the impedance of the device through high conductivity, but also optimize the signal-to-noise ratio and multi-functional processing ability of the artificial synaptic device through fine energy band regulation.

5 System Integration

5.1 Heterogeneous Integration

In traditional wearable devices with separate sensing, memory and computing, system integration usually depends on the interconnection of modular stack and printed circuit board (PCB). Physical signal acquisition, digital processing and algorithm operation are undertaken by independent hardware units, and the data path follows the serial topology structure of "sensor-ADC-signal processor-memory". The physiological signals in analog domain are pre-amplified and filtered by the sensor interface, and then input to the analog-to-digital converter for sampling and quantization, and the continuous signals are converted into discrete digital sequences. The digital signal is transmitted to a central processing unit (CPU) or a digital signal processor (DSP) through a universal serial bus, instruction decoding and arithmetic logic operation are performed under the framework of von Neumann, and the intermediate result or final eigenvalue is written into a memory for subsequent call through a system bus. This physically separated sensing, storage and computing unit leads to frequent Data Shuttling between modules. This process not only introduces significant RC delay, but also causes a lot of redundant power consumption, which is difficult to meet the demand of real-time processing of high-throughput physiological signals [99].

In order to break through the performance bottleneck of the separation architecture of sensing, memory and computing, heterogeneous integration has become the key path to connect new sensitive materials with the underlying silicon-based circuits. Its core lies in the deep integration of functional materials with excellent sensing-computing synergistic characteristics and CMOS circuits responsible for signal reading and processing through physical stacking or monolithic integration [100]. Monolithic 3D Integration uses van der Waals force to connect layers, which effectively reduces the parasitic capacitance between layers and the process thermal budget. By integrating the perceptual cortex with the computing substrate, some synaptic calculations can be performed in situ at the perceptual end, thus significantly reducing the power consumption and delay of data handling [101].

The concrete realization of this strategy is embodied in a monolithic three-dimensional heterogeneous integration paradigm: First, using a back-end-of-line compatible thermal budget as low as 180 °C, a MoS_2 channel is transferred onto prefabricated local back-gate islands, and $Al_2O_3/HfO_2/Al_2O_3$ is grown by atomic layer deposition as the floating gate dielectric, thereby constructing a bottom-layer MoS_2 memristive transistor network. Subsequently, through a 50 nm interconnect dielectric layer and vias, this network is vertically stacked with a top-layer In_2Se_3 photodetector [102]. This architecture not only takes advantage of the lossless transfer and heterogeneous integration of two-dimensional materials on atomically flat surfaces, effectively avoiding the high-temperature incompatibility of conventional CMOS processes, but also replaces the traditional resistive load with the non-volatile analog programmable characteristics of MoS_2 memristive transistors, thereby realizing dynamic on-chip calibration of the response non-uniformity of the In_2Se_3 photodetector array and effectively suppressing crosstalk current.

This heterogeneous integration paradigm brings significant advantages to wearable devices: on the one hand, the architecture eliminates long distance data transmission, greatly reduces system power consumption, and effectively prolongs the battery life of wearable devices [103]; on the other hand,

it simplifies system components through vertical spatial multiplexing, greatly promoting device miniaturization and light weighting [104].

5.2 Self-Powered Power Supply

To reduce the dependency on batteries in wearable intelligent systems, energy harvesting technologies based on piezoelectric and triboelectric effects are of critical importance. Breakthroughs in two-dimensional (2D) materials within this field have primarily focused on enhancing power output through defect engineering and structural design. Although bulk MoS_2 lacks piezoelectricity due to its centrosymmetric structure, this limitation is broken in monolayer MoS_2. However, monolayer MoS_2 grown via chemical vapor deposition (CVD) typically contains a high density of sulfur vacancy defects. These defects can trap charge carriers and screen the piezoelectric potential, leading to diminished output performance. In a 2018 study by Han et al. [105], a sulfur-treatment process was introduced to effectively fill sulfur vacancies within the lattice. The repaired monolayer MoS_2 exhibited an enhanced piezoelectric coefficient (d_{11} increased from 3.06 pm/V to 3.73 pm/V), with output voltage and current reaching more than twice and three times, respectively, those of the untreated sample.

5.3 Thermal Management System

As wearable electronics advance toward higher integration, multifunctionality, and miniaturization, the sharp increase in localized power density has led to the severe issue of "hotspots". For skin-conformal wearable devices, thermal management faces a dual challenge: on one hand, excessive temperature can degrade sensor sensitivity and shorten battery life (device reliability); on the other hand, human skin is highly sensitive to temperature, and a localized temperature rise exceeding 40 °C may cause thermal discomfort or even low-temperature burns (user thermal comfort).

While conventional metal- or carbon-based nanomaterials (such as graphene and carbon nanotubes) exhibit excellent thermal conductivity, their high electrical conductivity poses a significant risk of short circuits in compact flexible circuits and often compromises signal transmission stability. In contrast, hexagonal boron nitride (h-BN), a two-dimensional material with a wide bandgap (~5.9 eV), is recognized as an ideal candidate for addressing thermal management bottlenecks in flexible electronics due to its unique "high thermal conductivity yet electrical insulation" properties, earning it the nickname "white graphene".

The high thermal conductivity of h-BN originates from the small mass difference between boron (B) and nitrogen (N) atoms in its lattice, combined with strong covalent bonding, which significantly reduces phonon scattering [106]. The theoretical in-plane thermal conductivity of monolayer h-BN can reach up to 2,000 $W \cdot m^{-1} \cdot K^{-1}$. However, in practical polymer composite applications, h-BN exhibits notable anisotropy [107]. To maximize heat dissipation efficiency, research emphasis has shifted from simple random filling to the ordered regulation of microstructure. For example, by utilizing external fields (electric or magnetic) or rheological shear forces (such as in blade coating or spinning processes), h-BN nanosheets can be aligned along the direction of heat flow to construct efficient "phonon highways" [108]. Through methods like ice-templating or nickel-foam templating, continuous 3D h-BN frameworks can be fabricated, establishing three-dimensional thermal conduction networks that mitigate interfacial thermal resistance. This approach enables an order-of-magnitude enhancement in the thermal conductivity of polymer matrices even at low filler loadings [109].

Within the architectural hierarchy of wearable systems, h-BN primarily facilitates thermal management in two forms: Firstly, h-BN/polymer composites serve as thermal interface materials (TIMs) between the skin and the sensor or between the chip and the packaging layer, filling microscopic gaps and reducing contact thermal resistance. Compared to traditional oxide fillers like Al_2O_3, the two-dimensional layered structure of h-BN enables higher thermal conduction pathways at lower filler loadings, while simultaneously maintaining the flexibility and stretchability of the composite material. Secondly, h-BN-based in-plane heat spreading films can rapidly distribute heat from point sources evenly across the plane, thereby eliminating hot spots. Research demonstrates that modified nanocellulose or polyimide substrates incorporating h-BN can reduce the surface temperature of devices by 5–7 °C under continuous operation, significantly enhancing wearing safety.

Looking ahead to the 2025–2030 timeframe, the role of hexagonal boron nitride in wearable technology is undergoing a paradigm shift from a passive auxiliary component to a core enabler within the device architecture. To address the increasingly complex design space of hybrid composites, artificial intelligence and machine learning algorithms are progressively supplanting traditional trial-and-error methods, accelerating the discovery of optimal formulations by precisely predicting filler properties. Driven by this methodological innovation, future h-BN systems are expected to achieve two key breakthroughs: (1) the integration of active thermal management, utilizing h-BN's excellent thermal conductivity and electrical insulation as a substrate for flexible thermoelectric coolers; and (2) deep functional modality fusion, where h-BN will evolve into multifunctional electronic skin that integrates structural support, efficient heat dissipation, dielectric sensing, and antibacterial protection into a single, seamlessly integrated platform for next-generation long-term health monitoring devices.

6 Future Challenges

While two-dimensional materials have demonstrated superior electrical, thermal, and mechanical properties in single devices at the laboratory scale, translating them into clinically usable wearable systems still faces a significant leap. Current research and development focus is shifting from single-function "champion devices" to multifunctional, highly reliable "system-level integration". This requires not only breakthroughs at the material level but also solutions to the compatibility issues at heterogeneous material interfaces and the mechanical mismatch between hard and soft systems.

6.1 Key Challenges and Technological Bottlenecks

Scalability and Yield: Currently, high-quality two-dimensional materials still mainly rely on mechanical exfoliation or small-area CVD growth, and the transfer process often introduces polymer residues, wrinkles, and cracks. Achieving wafer-scale, low-defect-density direct growth and developing non-destructive roll-to-roll transfer technology are the primary obstacles to moving from the laboratory to industrialization.

Contact Resistance and Interface Engineering: Significant contact resistance and Fermi level pinning exist between extremely thin two-dimensional semiconductors and three-dimensional metal electrodes, severely limiting the drive current and frequency response of devices. Developing edge contact or van der Waals contact (vdW contact) techniques to reduce the Schottky barrier is essential for improving the signal-to-noise ratio of high-performance wearable sensors.

Environmental Stability and Encapsulation: Many two-dimensional materials (such as black phosphorus and some TMDs) are highly susceptible to oxidation in air, and even graphene is easily affected by environmental humidity, leading to performance drift. For wearable devices used in close contact with the skin for extended periods, developing encapsulation layers that are both water- and oxygen-barrier, and extremely thin without affecting mechanical flexibility (such as ultrathin h-BN or ALD oxides) is crucial for ensuring device lifespan. Furthermore, the corrosion of devices by biofluids (sweat, tissue fluid) is a real problem that must be addressed.

7 Conclusion

As wearable technology evolves from early-stage simple signal acquisition devices to highly integrated, adaptive, and intelligent systems, two-dimensional (2D) materials have emerged as a core material system driving this transformation, owing to their unique atomic-scale structure, high flexibility, tunable electronic and optical properties, multi-physics response characteristics, and excellent compatibility with interface engineering. From the high conductivity of graphene and the semiconducting properties of transition metal dichalcogenides (TMDs), to the metallic character and processability of MXenes, the insulating and thermal management capabilities of hexagonal boron nitride (h-BN), and the optoelectronic, chemical, and ionic functionalities exhibited by black phosphorus and other emerging 2D materials, this family provides a vast material foundation for constructing key modules such as multimodal sensing, intelligent actuation, flexible computing, self-powered energy sources, and communication interconnects.

At the functional level of intelligent systems, the intrinsic high sensitivity of 2D materials enables wearable sensors to achieve greater accuracy and faster response in physiological monitoring, motion analysis, and environmental detection. Leveraging their responsiveness to thermal, electrical, optical, and chemical stimuli, they facilitate softer and more natural human-machine interaction in soft actuators and haptic feedback systems. Through neuromorphic computing and heterostructure engineering, signal processing is gradually shifting towards the material and structural levels, offering a new device paradigm for low-power, real-time edge intelligence. In energy systems, 2D materials provide efficient energy management solutions for wearable platforms based on triboelectric, piezoelectric, photovoltaic, thermoelectric, and flexible energy storage devices. Augmented by textile structures, 3D porous architectures, and stretchable structural engineering, the advantages of 2D materials are gradually translated from the material level to system-level structural intelligence, realizing a new model of smart wearable systems where “structure is function”.

Nevertheless, the practical application of 2D materials in wearable systems still faces multiple challenges. These include issues related to large-scale material preparation and consistency, insufficient long-term stability in complex environments, mechanical reliability under large deformation and multi-cycle conditions, engineering difficulties in heterogeneous system integration, safety concerns regarding prolonged skin exposure, and the early exploratory stage of material-level artificial intelligence and data processing. However, with continuous improvements in fabrication processes, optimization of interface and encapsulation technologies, innovation in multi-scale structural design strategies, and the growing convergence of materials science and artificial intelligence, the application boundaries of 2D materials in wearable systems will continue to expand.

Overall, 2D materials are leading the transition of wearable technology from “functional wearables” to “intelligent wearables”, from a “device-centric” to a “human-centric” approach, and from “single-device optimization” to “system-level co-design”. Future wearable devices will not merely be electronic systems attached to the human body but will evolve into intelligent interfaces deeply integrated with human functions—such as “smart skin”, “functional textiles”, and even adaptive human interaction networks. In this process, the high flexibility, multimodality, and multi-scale synergy provided by 2D materials will serve as the key driving force propelling intelligent wearable systems toward their next-generation forms.

Funding

This work was supported by the STI 2030-Major Projects (Grant No. 2022ZD0209200), the National Natural Science Foundation of China (Grant No. 62374099), the Beijing Natural Science Foundation-Xiaomi Innovation Joint Fund (L233009), and the Independent Research Program of School of Integrated Circuits, Tsinghua University. This work was also supported by the Center of Nanofabrication, Tsinghua University.

Author Contributions

Jiayu Ma: Writing – original draft, Methodology, Formal analysis, Visualization, Data curation, Investigation. Lu Jin: Writing – review & editing, Data curation, Investigation. Zongmin Ma: Supervision, Funding acquisition, Writing – review & editing. He Tian: Supervision, Funding acquisition, Writing – review & editing.

Conflict of Interest

All the authors declare that they have no conflict of interest.

References

[1] Vos, T., Lim, S.S., Abbafati, C., Abbas, K.M., Abbasi, M., Abbasifard, M., Abbasi-Kangevari, M., Abbastabar, H., Abd-Allah, F., Abdelalim, A., *et al.*: Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. The lancet **396**(10258), 1204–1222 (2020). https://doi.org/10.1016/S0140-6736(20)30925-9

[2] Ates, H.C., Nguyen, P.Q., Gonzalez-Macia, L., Morales-Narváez, E., Güder, F., Collins, J.J., Dincer, C.: End-to-end design of wearable sensors. Nature Reviews Materials **7**(11), 887–907 (2022). https://doi.org/10.1038/s41578-022-00460-x

[3] Meng, K., Xiao, X., Wei, W., Chen, G., Nashalian, A., Shen, S., Xiao, X., Chen, J.: Wearable pressure sensors for pulse wave monitoring. Advanced Materials **34**(21), 2109357 (2022). https://doi.org/10.1002/adma.202109357

[4] Elgendi, M., Fletcher, R., Liang, Y., Howard, N., Lovell, N.H., Abbott, D., Lim, K., Ward, R.: The use of photoplethysmography for assessing hypertension. NPJ digital medicine **2**(1), 60 (2019). https://doi.org/10.1038/s41746-019-0136-7

[5] Zhao, Y.C., Wang, Z., Zhao, H., Yap, N.A., Wang, R., Cheng, W., Xu, X., Ju, L.A.: Sensing the future of thrombosis management: integrating vessel-on-a-chip models, advanced biosensors, and AI-driven digital twins. ACS Sensors **10**(3), 1507–1520 (2025). https://doi.org/10.1021/acssensors.4c02764

[6] Qileng, A., Chen, S., Zhou, M., Huang, H., Jiang, Z., Guo, H., Liu, Y., Xu, Z.-L.: The Rational Design of Pt Single Atoms-Bridged Nanozyme with Enhancing Direct Electron Transfer Pathway for Glucose Oxidation. Advanced Functional Materials **36**(1), e13194 (2026). https://doi.org/10.1002/adfm.202513194

[7] Li, Y., Chen, Y.: Review of noninvasive continuous glucose monitoring in diabetics. ACS Sensors **8**(10), 3659–3679 (2023). https://doi.org/10.1021/acssensors.3c01538

[8] Tang, K.W.K., Jeong, J., Hsieh, J.-C., Yao, M., Ding, H., Wang, W., Liu, X., Pyatnitskiy, I., He, W., Moscoso-Barrera, W.D., *et al.*: Bioadhesive hydrogel-coupled and miniaturized ultrasound transducer system for long-term, wearable neuromodulation. Nature Communications **16**(1), 4940 (2025). https://doi.org/10.1038/s41467-025-60181-x

[9] Um, H.-K., Noh, E., Yoo, C., Lee, H.W., Kang, J.-W., Lee, B.H., Lee, J.-R.: Mobile sleep stage analysis using multichannel wearable devices integrated with stretchable transparent electrodes. ACS Sensors **10**(6), 4016–4026 (2025). https://doi.org/10.1021/acssensors.4c03602

[10] Beg, S., Handa, M., Shukla, R., Rahman, M., Almalki, W.H., Afzal, O., Altamimi, A.S.A.: Wearable smart devices in cancer diagnosis and remote clinical trial monitoring: Transforming the healthcare applications. Drug discovery today **27**(10), 103314 (2022). https://doi.org/10.1016/j.drudis.2022.06.014

[11] Wang, L., Fu, X., He, J., Shi, X., Chen, T., Chen, P., Wang, B., Peng, H.: Application challenges in fiber and textile electronics. Advanced Materials **32**(5), 1901971 (2020). https://doi.org/10.1002/adma.201901971

[12] Chhowalla, M., Jena, D., Zhang, H.: Two-dimensional semiconductors for transistors. Nature Reviews Materials **1**(11), 16052 (2016). https://doi.org/10.1038/natrevmats.2016.52

[13] Heo, J.S., Hossain, M.F., Kim, I.: Challenges in design and fabrication of flexible/stretchable carbon-and textile-based wearable sensors for health monitoring: A critical review. Sensors **20**(14), 3927 (2020). https://doi.org/10.3390/s20143927

[14] Rivnay, J., Inal, S., Salleo, A., Owens, R.M., Berggren, M., Malliaras, G.G.: Organic electrochemical transistors. Nature Reviews Materials **3**(2), 17086 (2018). https://doi.org/10.1038/natrevmats.2017.86

[15] Fang, Y., Li, X., Fang, Y.: Organic bioelectronics for neural interfaces. Journal of Materials Chemistry C **3**(25), 6424–6430 (2015). https://doi.org/10.1039/C5TC00569H

[16] Chen, Z., Huang, Y., Zhang, B., Sun, D., Yu, X.: Deformable materials and structures in wearable haptic interfaces. Nature Reviews Materials **11**, 266–285 (2026). https://doi.org/10.1038/s41578-025-00877-0

[17] Geim, A.K., Novoselov, K.S.: The rise of graphene. Nature Materials **6**(3), 183–191 (2007). https://doi.org/10.1038/nmat1849

[18] Novoselov, K.S., Geim, A.K., Morozov, S.V., Jiang, D.-e., Zhang, Y., Dubonos, S.V., Grigorieva, I.V., Firsov, A.A.: Electric field effect in atomically thin carbon films. Science **306**(5696), 666–669 (2004). https://doi.org/10.1126/science.1102896

[19] Bhimanapati, G.R., Lin, Z., Meunier, V., Jung, Y., Cha, J., Das, S., Xiao, D., Son, Y., Strano, M.S., Cooper, V.R., *et al.*: Recent advances in two-dimensional materials beyond graphene. ACS Nano **9**(12), 11509–11539 (2015). https://doi.org/10.1021/acsnano.5b05556

[20] Naguib, M., Mashtalir, O., Carle, J., Presser, V., Lu, J., Hultman, L., Gogotsi, Y., Barsoum, M.W.: Two-dimensional transition metal carbides. ACS Nano **6**(2), 1322–1331 (2012). https://doi.org/10.1021/nn204153h

[21] Molle, A., Goldberger, J., Houssa, M., Xu, Y., Zhang, S.-C., Akinwande, D.: Buckled two-dimensional Xene sheets. Nature materials **16**(2), 163–169 (2017). https://doi.org/10.1038/nmat4802

[22] Goel, N., Kumar, R.: Physics of 2D materials for developing smart devices. Nano-Micro Letters **17**(1), 197 (2025). https://doi.org/10.1007/s40820-024-01635-7

[23] Aftab, S., Hussain, S., Al-Kahtani, A.A.: Latest innovations in 2D flexible nanoelectronics. Advanced Materials **35**(42), 2301280 (2023). https://doi.org/10.1002/adma.202301280

[24] Lee, C., Wei, X., Kysar, J.W., Hone, J.: Measurement of the elastic properties and intrinsic strength of monolayer graphene. Science **321**(5887), 385–388 (2008). https://doi.org/10.1126/science.1157996

[25] Lu, Y., Yang, G., Wang, S., Zhang, Y., Jian, Y., He, L., Yu, T., Luo, H., Kong, D., Xianyu, Y., *et al.*: Stretchable graphene–hydrogel interfaces for wearable and implantable bioelectronics. Nature Electronics **7**(1), 51–65 (2024). https://doi.org/10.1038/s41928-023-01091-y

[26] Qin, L., Wang, L.: Two-dimensional materials, the ultimate solution for future electronics and very-large-scale integrated circuits. Nano-Micro Letters **17**(1), 255 (2025). https://doi.org/10.1007/s40820-025-01769-2

[27] Huang, C., Yang, W., Wang, H., Huang, S., Gao, S., Li, D., Liu, J., Hou, S., Feng, W., Wang, Z., *et al.*: Flexible/Regenerative Nanosensor with Automatic Sweat Collection for Cytokine Storm Biomarker Detection. ACS Nano **18**(32), 21198–21210 (2024). https://doi.org/10.1021/acsnano.4c04456

[28] Li, W., Shen, J., Ma, Y., Xu, X., Chen, H., Yu, L., Ji, C., He, M., Ma, K., Duo, Y., *et al.*: 3D Crystal Construction by Single-Crystal 2D Material Supercell Multiplying. Advanced Science **12**(2), 2411656 (2025). https://doi.org/10.1002/advs.202411656

[29] Dcosta, J.V., Ochoa, D., Sanaur, S.: Recent progress in flexible and wearable all organic photoplethysmography sensors for SpO_2 monitoring. Advanced Science **10**(31), 2302752 (2023). https://doi.org/10.1002/advs.202302752

[30] Yuan, S., Deng, J., Li, L.: Manipulating 2D Nanomaterials: Shaping the Future of Intelligent Wearable Health Monitoring Devices. ACS Nano **20**(8), 6446–6492 (2026). https://doi.org/10.1021/acsnano.5c21609

[31] Hu, J., Dong, M.: Recent advances in two-dimensional nanomaterials for sustainable wearable electronic devices. Journal of Nanobiotechnology **22**(1), 63 (2024). https://doi.org/10.1186/s12951-023-02274-7

[32] Patil, J.J., Chae, W.H., Trebach, A., Carter, K.-J., Lee, E., Sannicolo, T., Grossman, J.C.: Failing forward: Stability of transparent electrodes based on metal nanowire networks. Advanced Materials **33**(5), 2004356 (2021). https://doi.org/10.1002/adma.202004356

[33] Hong, S.K., Kim, K.Y., Kim, T.Y., Kim, J.H., Park, S.W., Kim, J.H., Cho, B.J.: Electromagnetic interference shielding effectiveness of monolayer graphene. Nanotechnology **23**(45), 455704 (2012). https://doi.org/10.1088/0957-4484/23/45/455704

[34] Akinwande, D., Petrone, N., Hone, J.: Two-dimensional flexible nanoelectronics. Nature communications **5**(1), 5678 (2014). https://doi.org/10.1038/ncomms6678

[35] Castro Neto, A.H., Guinea, F., Peres, N.M., Novoselov, K.S., Geim, A.K.: The electronic properties of graphene. Reviews of modern physics **81**(1), 109–162 (2009). https://doi.org/10.1103/RevModPhys.81.109

[36] Kireev, D., Sel, K., Ibrahim, B., Kumar, N., Akbari, A., Jafari, R., Akinwande, D.: Continuous cuffless monitoring of arterial blood pressure via graphene bioimpedance tattoos. Nature nanotechnology **17**(8), 864–870 (2022). https://doi.org/10.1038/s41565-022-01145-w

[37] Sanchez, V.C., Jachak, A., Hurt, R.H., Kane, A.B.: Biological interactions of graphene-family nanomaterials: an interdisciplinary review. Chemical research in toxicology **25**(1), 15–34 (2012). https://doi.org/10.1021/tx200339h

[38] Malaki, M., Varma, R.S.: Wetting of MXenes and beyond. Nano-Micro Letters **15**(1), 116 (2023). https://doi.org/10.1007/s40820-023-01049-x

[39] Huang, C., Chen, Y., Zhang, T., Gao, E., Wang, Y., Xia, G., Li, M., Lian, W., Deng, X., Wan, S., *et al.*: Continuous MXene fibers with near-gigapascal tensile strength via radial confinement and axial stretching. Nature Communications **17**, 1277 (2026). https://doi.org/10.1038/s41467-025-68038-z

[40] Thakur, A., Kim, J., Wyatt, B.C., Gogotsi, Y., Anasori, B.: Composition–structure–property relationships in MXenes. Nature Reviews Materials, 1–16 (2026). https://doi.org/10.1038/s41578-026-00911-9

[41] Xia, Y., Zha, J., Huang, H., Wang, H., Yang, P., Zheng, L., Zhang, Z., Yang, Z., Chen, Y., Chan, H.P., *et al.*:

Uncovering the Role of Crystal Phase in Determining Nonvolatile Flash Memory Device Performance Fabricated from$MoTe_2$-Based 2D van der Waals Heterostructures. ACS Applied Materials & Interfaces **15**(29), 35196–35205 (2023). https://doi.org/10.1021/acsami.3c06316

[42] Chhowalla, M., Shin, H.S., Eda, G., Li, L.-J., Loh, K.P., Zhang, H.: The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. Nature Chemistry **5**(4), 263–275 (2013). https://doi.org/10.1038/nchem.1589

[43] Hong, J., Hu, Z., Probert, M., Li, K., Lv, D., Yang, X., Gu, L., Mao, N., Feng, Q., Xie, L., *et al.*: Exploring atomic defects in molybdenum disulphide monolayers. Nature communications **6**(1), 6293 (2015). https://doi.org/10.1038/ncomms7293

[44] Mak, K.F., Lee, C., Hone, J., Shan, J., Heinz, T.F.: Atomically Thin MoS_2: A New Direct-Gap Semiconductor. Physical review letters **105**(13), 136805 (2010). https://doi.org/10.1103/PhysRevLett.105.136805

[45] Splendiani, A., Sun, L., Zhang, Y., Li, T., Kim, J., Chim, C.-Y., Galli, G., Wang, F.: Emerging photoluminescence in monolayer MoS_2. Nano letters **10**(4), 1271–1275 (2010). https://doi.org/10.1021/nl903868w

[46] Liu, X., Zhu, J., Shan, Y., Liu, C., Pan, C., Zhang, T., Liu, C., Chen, T., Ling, J., Duan, J., *et al.*: An ultrasensitive and broad-spectrum MoS_2 photodetector with extrinsic response using surrounding homojunction. Advanced Science **11**(45), 2408299 (2024). https://doi.org/10.1002/advs.202408299

[47] Hwang, S.-W., Tao, H., Kim, D.-H., Cheng, H., Song, J.-K., Rill, E., Brenckle, M.A., Panilaitis, B., Won, S.M., Kim, Y.-S., *et al.*: A physically transient form of silicon electronics. Science **337**(6102), 1640–1644 (2012). https://doi.org/10.1126/science.1226325

[48] Ling, X., Wang, H., Huang, S., Xia, F., Dresselhaus, M.S.: The renaissance of black phosphorus. Proceedings of the National Academy of Sciences **112**(15), 4523–4530 (2015). https://doi.org/10.1073/pnas.1416581112

[49] Tran, V., Soklaski, R., Liang, Y., Yang, L.: Layer-controlled band gap and anisotropic excitons in few-layer black phosphorus. Physical Review B **89**(23), 235319 (2014). https://doi.org/10.1103/PhysRevB.89.235319

[50] Shao, J., Xie, H., Huang, H., Li, Z., Sun, Z., Xu, Y., Xiao, Q., Yu, X.-F., Zhao, Y., Zhang, H., *et al.*: Biodegradable black phosphorus-based nanospheres for in vivo photothermal cancer therapy. Nature Communications **7**, 12967 (2016). https://doi.org/10.1038/ncomms12967

[51] Xia, F., Wang, H., Jia, Y.: Rediscovering black phosphorus as an anisotropic layered material for optoelectronics and electronics. Nature Communications **5**, 4458 (2014). https://doi.org/10.1038/ncomms5458

[52] Trushkov, Y., Perebeinos, V.: Phonon-limited carrier mobility in monolayer black phosphorus. Physical Review B **95**(7), 075436 (2017). https://doi.org/10.1103/PhysRevB.95.075436

[53] Zhang, Y., Wang, L., Zhao, L., Wang, K., Zheng, Y., Yuan, Z., Wang, D., Fu, X., Shen, G., Han, W.: Flexible self-powered integrated sensing system with 3D periodic ordered black phosphorus@MXene thin-films. Advanced Materials **33**(22), 2007890 (2021). https://doi.org/10.1002/adma.202007890

[54] Island, J.O., Steele, G.A., Zant, H.S.J., Castellanos-Gomez, A.: Environmental instability of few-layer black phosphorus. 2D Materials **2**(1), 011002 (2015). https://doi.org/10.1088/2053-1583/2/1/011002

[55] Bansil, A., Lin, H., Das, T.: Colloquium: Topological band theory. Reviews of Modern Physics **88**(2), 021004 (2016). https://doi.org/10.1103/RevModPhys.88.021004

[56] Amorim, R.G., Scheicher, R.H.: Silicene as a new potential DNA sequencing device. Nanotechnology **26**(15), 154002 (2015). https://doi.org/10.1088/0957-4484/26/15/154002

[57] Xue, T., Liang, W., Li, Y., Sun, Y., Xiang, Y., Zhang, Y., Dai, Z., Duo, Y., Wu, L., Qi, K., *et al.*: Ultrasensitive detection of miRNA with an antimonene-based surface plasmon resonance sensor. Nature communications **10**(1), 28 (2019). https://doi.org/10.1038/s41467-018-07947-8

[58] Tao, W., Kong, N., Ji, X., Zhang, Y., Sharma, A., Ouyang, J., Qi, B., Wang, J., Xie, N., Kang, C., *et al.*: Emerging two-dimensional monoelemental materials (Xenes) for biomedical applications. Chemical Society Reviews **48**(11), 2891–2912 (2019). https://doi.org/10.1039/c8cs00823j

[59] Illarionov, Y.Y., Knobloch, T., Jech, M., Lanza, M., Akinwande, D., Vexler, M.I., Mueller, T., Lemme, M.C., Fiori, G., Schwierz, F., *et al.*: Insulators for 2D nanoelectronics: the gap to bridge. Nature Communications **11**, 3385 (2020). https://doi.org/10.1038/s41467-020-16640-8

[60] Watanabe, K., Taniguchi, T., Kanda, H.: Direct-bandgap properties and evidence for ultraviolet lasing of hexagonal boron nitride single crystal. Nature Materials **3**(6), 404–409 (2004). https://doi.org/10.1038/nmat1134

[61] Cassabois, G., Valvin, P., Gil, B.: Hexagonal boron nitride is an indirect bandgap semiconductor. Nature Photonics **10**(4), 262–266 (2016). https://doi.org/10.1038/nphoton.2015.277

[62] Giovannetti, G., Khomyakov, P.A., Brocks, G., Kelly, P.J., Brink, J.: Substrate-induced band gap in graphene on hexagonal boron nitride: Ab initio density functional calculations. Physical Review B **76**(7), 073103 (2007). https://doi.org/10.1103/PhysRevB.76.073103

[63] Jaffe, G.R., Smith, K.J., Watanabe, K., Taniguchi, T., Lagally, M.G., Eriksson, M.A., Brar, V.W.: Thickness-dependent cross-plane thermal conductivity measurements of exfoliated hexagonal boron nitride. ACS Applied Materials & Interfaces **15**(9), 12545–12550 (2023). https://doi.org/10.1021/acsami.2c21306

[64] Lee, G.-H., Yu, Y.-J., Cui, X., Petrone, N., Lee, C.-H., Choi, M.S., Lee, D.-Y., Lee, C., Yoo, W.J., Watanabe, K., *et al.*: Flexible and transparent MoS_2 field-effect transistors on hexagonal boron nitride-graphene heterostructures. ACS Nano **7**(9), 7931–7936 (2013). https://doi.org/10.1021/nn402954e

[65] Chen, X., Lu, X., Deng, B., Sinber, O., Shalom, Y., Li, Q., Dean, C., Taniguchi, T., Watanabe, K., Xia, F.: Widely tunable black phosphorus mid-infrared photodetector. Nature Communications **8**, 1672 (2017). https://doi.org/10.1038/s41467-017-01978-3

[66] Jang, S.K., Youn, J., Song, Y.J., Lee, S.: Synthesis and characterization of hexagonal boron nitride as a gate dielectric. Scientific Reports **6**, 30449 (2016). https://doi.org/10.1038/srep30449

[67] Jamshidnejad-Tosaramandani, T., Kashanian, S., Omidfar, K., Schiöth, H.B.: The Role of Nanomaterials in the Wearable Electrochemical Glucose Biosensors for Diabetes Management. Biosensors **15**(7), 451 (2025). https://doi.org/10.3390/bios15070451

[68] Park, S., Boo, H., Chung, T.D.: Electrochemical non-enzymatic glucose sensors. Analytica Chimica Acta **556**(1), 46–57 (2006). https://doi.org/10.1016/j.aca.2005.05.080

[69] Lei, Y., Zhao, W., Zhang, Y., Jiang, Q., He, J.-H., Baeumner, A.J., Wolfbeis, O.S., Wang, Z.L., Salama, K.N., Alshareef, H.N.: A MXene-Based Wearable Biosensor System for High-Performance In Vitro Perspiration Analysis. Small **15**(19), 1901190 (2019). https://doi.org/10.1002/smll.201901190

[70] Zhang, W., Jiang, S., Yu, H., Feng, S., Zhang, K.: Ga@MXene-based flexible wearable biosensor for glucose monitoring in sweat. iScience **28**(2), 111737 (2025). https://doi.org/10.1016/j.isci.2024.111737

[71] Li, Q.-F., Chen, X., Wang, H., Liu, M., Peng, H.-L.: Pt/MXene-Based Flexible Wearable Non-Enzymatic Electrochemical Sensor for Continuous Glucose Detection in Sweat. ACS Applied Materials & Interfaces **15**(10), 13290–13298 (2023). https://doi.org/10.1021/acsami.2c20543

[72] Min, S., Geng, H., He, Y., Xu, T., Liu, Q., Zhang, X.: Minimally and non-invasive glucose monitoring: the road toward commercialization. Sensors & Diagnostics **4**, 370–396 (2025). https://doi.org/10.1039/D4SD00360H

[73] Yang, T., Jiang, X., Huang, Y., Tian, Q., Zhang, L., Dai, Z., Zhu, H.: Mechanical sensors based on two-dimensional materials: Sensing mechanisms, structural designs and wearable applications. iScience **25**(1), 103728 (2022). https://doi.org/10.1016/j.isci.2021.103728

[74] Falin, A., Cai, Q., Santos, E., Scullion, D., Qian, D., Zhang, R., Yang, Z., Huang, S., Watanabe, K., Taniguchi, T., *et al.*: Mechanical properties of atomically thin boron nitride and the role of interlayer interactions. Nature Communications **8**, 15815 (2017). https://doi.org/10.1038/ncomms15815

[75] Androulidakis, C., Zhang, K., Robertson, M., Tawfick, S.: Tailoring the mechanical properties of 2D materials and heterostructures. 2D Materials **5**(3), 032005 (2018). https://doi.org/10.1088/2053-1583/aac764

[76] Zhang, J., Sun, T., Liu, L., Niu, S., Wang, K., Song, H., Han, Q., Han, Z., Ren, L., Lin, Q.: Flexible and highly sensitive pressure sensors based on microcrack arrays inspired by scorpions. RSC Advances **9**, 22740–22748 (2019). https://doi.org/10.1039/C9RA03663F

[77] Yang, T., Zhong, Y., Tao, D., Li, X., Zang, X., Lin, S., Jiang, X., Li, Z., Zhu, H.: Integration of graphene sensor with electrochromic device on modulus-gradient polymer for instantaneous strain visualization. 2D Materials **4**(3), 035020 (2017). https://doi.org/10.1088/2053-1583/aa78cc

[78] Yang, T., Wang, W., Huang, Y., Jiang, X., Zhao, X.: Accurate Monitoring of Small Strain for Timbre Recognition via Ductile Fragmentation of Functionalized Graphene Multilayers. ACS Applied Materials & Interfaces **12**(51), 57352–57361 (2020). https://doi.org/10.1021/acsami.0c16855

[79] Liu, H., Chen, X., Zheng, Y., Zhang, D., Zhao, Y., Wang, C., Pan, C., Liu, C., Shen, C.: Lightweight, Superelastic, and Hydrophobic Polyimide Nanofiber /MXene Composite Aerogel for Wearable Piezoresistive Sensor and Oil/Water Separation Applications. Advanced Functional Materials **31**(13), 2008006 (2021). https://doi.org/10.1002/adfm.202008006

[80] Zheng, Y., Yin, R., Zhao, Y., Liu, H., Zhang, D., Shi, X., Zhang, B., Liu, C., Shen, C.: Conductive

MXene/cotton fabric based pressure sensor with both high sensitivity and wide sensing range for human motion detection and E-skin. Chemical Engineering Journal **420**, 127720 (2021). https://doi.org/10.1016/j.cej.2020.127720

[81] Chao, M., He, L., Gong, M., Li, N., Li, X., Peng, L., Shi, F., Zhang, L., Wan, P.: Breathable $Ti_3C_2T_x$ MXene/Protein Nanocomposites for Ultrasensitive Medical Pressure Sensor with Degradability in Solvents. ACS Nano **15**(6), 9746–9758 (2021). https://doi.org/10.1021/acsnano.1c00472

[82] Choi, W., Kim, J., Lee, E., Mehta, G., Prasad, V.: Asymmetric 2D MoS_2 for Scalable and High-Performance Piezoelectric Sensors. ACS Applied Materials & Interfaces **13**(11), 13596–13603 (2021). https://doi.org/10.1021/acsami.1c00650

[83] Wang, H., Zhao, Z., Liu, P., Guo, X.: Laser-induced porous graphene on Polyimide/PDMS composites and its kirigami-inspired strain sensor. Theoretical and Applied Mechanics Letters **11**(2), 100240 (2021). https://doi.org/10.1016/j.taml.2021.100240

[84] Meng, K., Xiao, X., Liu, Z., Shen, S., Tat, T., Wang, Z., Lu, C., Ding, W., He, X., Yang, J.: Kirigami-Inspired Pressure Sensors for Wearable Dynamic Cardiovascular Monitoring. Advanced Materials **34**(36), 2202478 (2022). https://doi.org/10.1002/adma.202202478

[85] Li, M.-Z., Han, S.-T., Zhou, Y.: Recent advances in flexible field-effect transistors toward wearable sensors. Advanced intelligent systems **2**(11), 2000113 (2020). https://doi.org/10.1002/aisy.202000113

[86] Verma, S., Kumar, A., Baghel, R., Verma, M.L.: Sc-doped SnS_2 monolayer-based promising biosensor FET for lung cancer early diagnosis: an ab-initio study. Journal of Nanoparticle Research **25**(7), 130 (2023). https://doi.org/10.1007/s11051-023-05783-6

[87] Chabchoubi, I.B., Belkhamssa, N., Ksibi, M., Hentati, O.: Trends in the detection of pharmaceuticals and endocrine-disrupting compounds by Field-Effect Transistors (FETs). Trends in Environmental Analytical Chemistry **30**, e00127 (2021). https://doi.org/10.1016/j.teac.2021.e00127

[88] Hideshima, S., Saito, M., Fujita, K., Harada, Y., Tsuna, M., Sekiguchi, S., Kuroiwa, S., Nakanishi, T., Osaka, T.: Label-free detection of allergens in food via surfactant-induced signal amplification using a field effect transistor-based biosensor. Sensors and Actuators B: Chemical **254**, 1011–1016 (2018). https://doi.org/10.1016/j.snb.2017.07.187

[89] Sengupta, J., Hussain, C.M.: Graphene-based electrochemical nano-biosensors for detection of SARS-CoV-2. Inorganics **11**(5), 197 (2023). https://doi.org/10.3390/inorganics11050197

[90] Wang, C.-S., Jiang, Y., Li, Z., Kong, F.-Y., Wang, W., Zhao, W.-W.: Graphene Photoelectrochemical Transistor for Dual-Directional Signal-on Biosensing. Advanced Functional Materials **35**(30), 2500235 (2025). https://doi.org/10.1002/adfm.202500235

[91] Schranghamer, T.F., Sharma, M., Singh, R., Das, S.: Review and comparison of layer transfer methods for two-dimensional materials for emerging applications. Chemical Society Reviews **50**(19), 11032–11054 (2021). https://doi.org/10.1039/d1cs00706h

[92] Manzeli, S., Ovchinnikov, D., Pasquier, D., Yazyev, O.V., Kis, A.: 2D transition metal dichalcogenides. Nature Reviews Materials **2**(8), 17033 (2017). https://doi.org/10.1038/natrevmats.2017.33

[93] Chen, Y., Pham, T., Mulchandani, A.: 2D MoS_2-based flexible optoelectronic for biosensing. Sensors and Actuators B: Chemical **439**, 137848 (2025). https://doi.org/10.1016/j.snb.2025.137848

[94] Wang, B., Sun, Y., Ding, H., Zhao, X., Zhang, L., Bai, J., Liu, K.: Bioelectronics-related 2D materials beyond graphene: fundamentals, properties, and applications. Advanced Functional Materials **30**(46), 2003732 (2020). https://doi.org/10.1002/adfm.202003732

[95] Gao, Y., Wang, S., Wang, B., Jiang, Z., Fang, T.: Recent progress in phase regulation, functionalization, and biosensing applications of polyphase MoS_2. Small **18**(34), 2202956 (2022). https://doi.org/10.1002/smll.202202956

[96] Fa, Y., Buttberg, M., Ran, K., Ahmad, R.W., Braun, D., Völkel, L., Lee, J., Cruces, S., Macco, B., Canto, B., et al.: Intermediate Resistive State in Wafer-Scale Vertical MoS_2 Memristors Through Lateral Silver Filament Growth for Artificial Synapse Applications. Advanced Functional Materials, e26682 (2025). https://doi.org/10.1002/adfm.202526682

[97] Fan, W., Yan, H., Wang, X., Tong, L., Yan, W., Su, C., Wang, Q., Yin, S.: Polarization-sensitive photosynapse based on PdSe2/WS2 heterostructure for visible-infrared broadband artificial vision system. Advanced Functional Materials **35**(43), 2416703 (2025). https://doi.org/10.1002/adfm.202416703

[98] Tang, Z., Chen, Z.-J., Fang, J.-L., Qiu, F., Wu, Y.-X., Jiang, Y.-P., Tang, X.-G., Li, S.-F., Lei, Z., Xu, X., *et al.*: An Optoelectronic Artificial Synapse Based on MXene/$CuInS_2$ Memristor for Novel Logical Operations and Neural Morphology Calculation. Advanced Optical Materials **14**(3), e01999 (2026). https://doi.org/10.1002/adom.202501999

[99] Xu, H., Xu, Z., Ren, Q., Meng, Y., Han, S., Wang, Z., Chai, Y., Bae, S.-H., Hu, W.: Two-dimensional materials for integrated sensing. Nature Materials, 1–15 (2026). https://doi.org/10.1038/s41563-026-02551-4

[100] Shen, Z., Shen, J., Sheng, H., Kang, L., Zeng, Z., Chen, W., Li, A., Zhao, C.: Heterogeneous Integration Strategies of Beyond-von Neumann Neuromorphic Electronics for Sensory in-Memory Computing. Advanced Functional Materials **36**(39), e31922 (2026). https://doi.org/10.1002/adfm.202531922

[101] Zhang, G., Luo, Q., Yao, J., Zhong, S., Wang, H., Xue, F., Yu, B., Loh, K.P., Zhang, Y.: All-in-one neuromorphic hardware with 2D material technology: current status and future perspective. Chemical Society Reviews **54**(18), 8196–8242 (2025). https://doi.org/10.1039/D5CS00251F

[102] Chowdhury, A., Rasyotra, A., Ravichandran, H., Manoharan, D.K., Sun, Y., Chen, C., Redwing, J.M., Yang, Y., Das, S.: 3D Integration of functionally diverse 2D materials for optoelectronic reservoir computing. Nature communications **16**(1), 10252 (2025). https://doi.org/10.1038/s41467-025-65109-z

[103] Gao, K., Sun, B., Cao, Z., Wang, M., Zhang, J., Wang, K., Zhou, G., Lu, Z., Shao, J.: Brain-Inspired Computing Based on Large-Scale Memristor Crossbar Arrays. Advanced Functional Materials **36**(32), e28309 (2026). https://doi.org/10.1002/adfm.202528309

[104] Liu, L., Kong, L., Li, Q., He, C., Ren, L., Tao, Q., Yang, X., Lin, J., Zhao, B., Li, Z., *et al.*: Transferred van der Waals metal electrodes for sub-1-nm MoS_2 vertical transistors. Nature Electronics **4**(5), 342–347 (2021). https://doi.org/10.1038/s41928-021-00566-0

[105] Han, S.A., Kim, T.-H., Kim, S.K., Lee, K.H., Park, H.-J., Lee, J.-H., Kim, S.-W.: Point-Defect-Passivated MoS2 Nanosheet-Based High Performance Piezoelectric Nanogenerator. Advanced Materials **30**(21), 1800342. https://doi.org/10.1002/adma.201800342

[106] Weng, Q., Wang, X., Wang, X., Bando, Y., Golberg, D.: Functionalized hexagonal boron nitride nanomaterials: emerging properties and applications. Chemical Society Reviews **45**(14), 3989–4012 (2016). https://doi.org/10.1039/C5CS00869G

[107] Jiang, P., Qian, X., Yang, R., Lindsay, L.: Anisotropic thermal transport in bulk hexagonal boron nitride. Physical Review Materials **2**(6), 064005 (2018). https://doi.org/10.1103/PhysRevMaterials.2.064005

[108] Wu, W., Zheng, M., Lu, K., Liu, F., Song, Y., Liu, Y.: Thermally conductive composites based on hexagonal boron nitride nanosheets for thermal management: fundamentals to applications. Composites Part A: Applied Science and Manufacturing **169**, 107533 (2023). https://doi.org/10.1016/j.compositesa.2023.107533

[109] Han, G., Cheng, H., Feng, Y., Zhang, S., Dong, J., Zhou, B., Liu, X., Liu, C., Tao, G., Shen, C.: Efficient thermal management of electronic devices by constructing interlayer phonon bridges. Nature Communications **16**(1), 10533 (2025). https://doi.org/10.1038/s41467-025-65554-w