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Two-Dimensional Material Multifunctional Integrated Devices for Intelligent Sensing Systems: From Basic Sensing to Neuromorphic Computing

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Abstract: Intelligent sensing systems are the core of the Internet of Things and human-computer interaction, and there is an urgent need for multi-functional integration, low power consumption, and miniaturization of devices. Two-dimensional materials provide an ideal platform for the integration of sensing, energy storage, and computing. This article reviews the latest progress in multifunctional integrated devices based on two-dimensional materials in sensing, micro energy storage and neuromorphic computing, analyzes the integrated applications driven by the intrinsic properties of materials, explores device co-design strategies, refines the "structure-material-algorithm" innovation paradigm, and looks forward to challenges and directions.

Keywords: Two-dimensional materials; Multi-functional integration; Intelligent sensing; Neuromorphic computing; Flexible sensors; Micro-supercapacitors; Heterogeneous structures

1. Introduction

1.1. Core requirements and technical bottlenecks of intelligent sensing systems

The integration of the Internet of Things and artificial intelligence promotes the widespread application of intelligent sensing systems, which, as "sensory nerves" directly determine the performance of upper-level decision-making [1–3]. Real-time sensing-processing-response closed loop has become a necessity, but the traditional discrete architecture has three core bottlenecks as follows:

(1) Low energy efficiency: Data transmission energy consumption in wireless sensor nodes accounts for more than 70% of the total energy consumption, and edge computing power and battery are limited [3–5];

(2) High latency: The cloud processing model cannot meet the millisecond-level real-time interaction requirements of industry, medical and other industries [6,7];

(3) Poor morphological adaptation: There is a mechanical mismatch between hard devices and biological tissues, making it difficult to achieve conformal attachment and stable signal acquisition [8,9].

Multifunctional integration has become an inevitable trend, and it is necessary to achieve "sensor-storage-computing" integration and heterogeneous integration to provide a broad application space for two-dimensional material devices [4,5].

1.2. Core advantages of two-dimensional materials

Two-dimensional materials have become an ideal platform for multi-functional integration due to their atomic thickness, excellent electrical properties, and rich physical effects. Graphene, MoS_2, and VO_2 are typical representatives. The core characteristics are compared in **Table 1**.

Table 1. Electrical conductivity, bandgap characteristics, and core features of representative two-dimensional functional materials

Material	Conductivity	Bandgap	Core features
Graphene	Ultra high (200,000 cm^2/Vs)	Zero	Flexibility, piezoresistive effect, high specific surface area
MoS_2	Medium	Single layer direct band gap (1.8 eV)	Piezoelectric effect, layer-dependent photoelectric properties
VO_2	Adjustable	Phase change mutation	68°C reversible insulation-metal transformation, multi-stimulus response

Van der Waals heterostructures can be stacked arbitrarily without dangling bonds, producing synergistic effects such as charge transfer and energy band regulation, and achieving multifunctional atomic-level integration [10–13].

2. Basic characteristics and integration mechanism of two-dimensional materials

2.1. Flexibility and mechanical conformality

Atomic-level thickness is the core of the flexibility of two-dimensional materials. The bending strain formula $\varepsilon=t/(2R+t)$ shows that reducing the thickness to the sub-nanometer level can significantly reduce strain and inhibit cracks. Graphene has a Young's modulus of about 1 TPa and an elastic strain limit of 20%. It can be conformally attached to any surface and is suitable for wearable and implantable scenarios.

2.2. Piezoelectric and piezoresistive effects

For the piezoelectric effect, the non-centrosymmetric structure (single-layer MoS_2) achieves direct conversion of mechanical strain to electrical signal, odd-numbered layers maintain piezoelectricity, and even-numbered layers have a piezoelectric effect that disappears [14–17]. For piezoresistive effect, strain modulation band changes resistance, the graphene gauge coefficient can reach hundreds, used for vibration and strain sensing [15].

2.3. Phase transition behavior

VO_2 undergoes a reversible insulation-to-metal transition at 68°C, with a resistivity mutation of 4–5 orders of magnitude. It can be triggered by heat, electricity, light, and strain, and has both highly sensitive sensing and intrinsic memory properties [10]. MoS_2 can achieve 2H-1T phase transition and regulate conductivity and electrochemical activity [18,19].

2.4. Heterogeneous structure synergy effect

Van der Waals stacking realizes atomic-level heterogeneous interfaces, and the core synergistic effect is as follows:

(1) Charge transfer: Fermi level alignment forms a built-in electric field to regulate carrier concentration [16];

(2) Energy band alignment: Type II heterojunction promotes the separation of photogenerated carriers and improves photoelectric performance [20–29].

For typical cases, graphene/VO_2 heterojunction realizes optoelectronic reconfigurable synaptic devices [29].

2.5. Photoelectric and electrical control characteristics

Single-layer MoS_2, etc. have a direct band gap, the exciton effect enhances light-matter interaction, and the photoelectric responsivity reaches 10^2–10^3 A/W [20,21]. The carrier concentration and type of two-dimensional materials can be controlled through gate voltage and defect engineering to adapt to logic and neuromorphic devices [23].

3. Sensor devices based on two-dimensional materials

3.1. Physical sensors

Two-dimensional materials can achieve highly sensitive detection of strain, temperature, humidity, etc. The core properties are showed in **Table 2**.

Table 2. Performance characteristics of representative two-dimensional material-based sensors

Sensor type	Material	Key performance	Reference
Pressure sensor	Graphene	Sensitivity 0.12 kPa^{-1},0-1.0 kPa	[34]
Strain sensor	MXene	GF > 178,0-53%	[34]
Temperature sensor	MoS_2	Sensitivity - 0.98% $°C^{-1}$,30-50°C	[34]
Humidity sensor	GO	Detection range 11–97% RH	[34]

The single-layer graphene bionic cilia vibration sensor can achieve highly sensitive detection of weak vibrations and is resistant to high temperature environments [16].

3.2. Chemical and gas sensors

The high specific surface area of two-dimensional materials provides abundant active sites, enabling detection through gas molecule-material charge transfer. Graphene and MoS_2 have detection limits of NO_2 and NH_3 at the ppb level; $Ti_3C_2T_X$ MXene can detect 50 ppb NH_3 at room temperature, and surface engineering can further improve performance [24].

3.3. Photoelectric sensor

Direct bandgap-adapted photodetection of single-layer TMDs with van der Waals heterojunctions extending broad spectral response. The MoS_2/WS_2 heterojunction inhibits carrier recombination and improves the responsivity; VO_2 photoinduced phase change can realize light-controlled conductance modulation and is suitable for light-controlled synapses [20,29].

3.4. Multi-modal sensing and signal decoupling

A single device can respond to multiple stimuli, and machine learning enables signal decoupling. The PEDOT:PSS/CNTs dual-mode sensor accurately separates temperature and humidity signals through algorithms; a single graphene oxide device can simultaneously detect temperature, humidity, pressure, and light intensity [22].

4. Energy storage integration: Micro supercapacitors

4.1. Requirements for self-powered systems

Wearable and IoT nodes require lightweight and flexible energy storage devices. Two-dimensional materials have both energy harvesting and electrode functions to support self-powered systems. The integration of wireless charging coils, micro supercapacitors and humidity sensors enables self-powered operation of the respiratory monitoring system [26].

4.2. Micro supercapacitor material system

The characteristics of materials are as outlined:

1. Graphene: High specific surface area and conductivity, mainly double-layer capacitance, laser-induced graphene can quickly prepare micro devices [27];
2. MoS_2: Edges and defects provide pseudocapacitance, and the 1T phase is more active than the 2H phase [27];
3. Graphene/TMDC composite: Combining high conductivity and high pseudocapacitance, the rate performance and stability are better than those of a single component [27].

5. Neuromorphic devices

5.1. Physical mechanism of artificial synapse

Artificial synapses simulate the plasticity of biological synapses and break through the bottleneck of the von Neumann architecture. Advantages of two-dimensional materials include atomically thin, easy to integrate heterogeneously, respond to multiple physical fields, and adapt to mechanisms such as resistive switching, floating gate, phase change, and ferroelectricity [28].

5.2. Typical devices

The two synapses are as follows:

1. Floating gate synapse: MoS_2/h-BN/graphene heterojunction achieves 20 ns programming, 10^6 cycles, and energy consumption of 18 fJ/pulse [28];
2. VO_2 phase change synapse: Multi-stimulus response, picojoule-level energy consumption, intrinsic memory, graphene/VO_2 heterojunction achieves LTP/LTD bidirectional modulation [28,29].

5.3. Perceptual neuromorphic systems

"In-sense computing" integrates perception and computing to avoid data transfer losses. The MoS_2 tactile array + synaptic transistor realizes in-sensory processing of pressure signals; the photodetector array can directly complete the convolution operation and reduce power consumption [25,28].

6. “Structure-Material-Algorithm” multi-dimensional innovation

The innovations and integration are as follows:

(1) Structural innovation: Vertical heterostructures shorten carrier paths and increase integration density; torsion angle control induces Moiré superlattice; three-dimensional integration greatly improves functional density and is suitable for neuromorphic chips [28,29];

(2) Material innovation: Defect engineering regulates carrier and interface properties; gas-receptor synergy greatly improves the resistance-to-switch ratio of memristors; ferroelectric coupling realizes multi-modal synaptic behavior [29–32];

(3) Algorithm innovation: Machine learning is used for multi-modal signal decoupling, in-sense processing and rapid material screening; 1DCNN algorithm assists graphene vibration sensors to achieve directional decoupling and pattern recognition [22,31];

(4) Wireless power supply integration: Inductive coupling, radio frequency acquisition, piezoelectric/triboelectric power generation realize wireless power supply, and two-dimensional material self-powered devices can build permanently operating wireless sensing nodes.

7. Typical application scenarios

Several scenarios are as follows:

(1) Wearable health monitoring: Graphene smart contact lenses diagnose ocular surface inflammation; diabetes patches integrate multiple sensors and microneedles to achieve blood glucose monitoring and closed-loop drug delivery; the signal-to-noise ratio of MXene ECG/EMG electrodes is better than commercial electrodes [14];

(2) Human-computer interaction: MXene artificial eardrum has a detection limit of 0.1 Pa and a speech recognition accuracy of 96.4%; wearable sensors realize gesture and whole-body motion capture; artificial pain receptors simulate biological pain responses and are adapted to smart prostheses [14,31,32].

(3) Environmental monitoring: Two-dimensional material gas sensors realize ppb-level pollutant detection; triboelectric nanogenerators drive self-powered nodes and combine with radio frequency acquisition to build a permanent environmental monitoring network [14,24].

8. Challenges and prospects

8.1. Core challenges

The core challenges are as listed:

(1) Material scale-up: Wafer-level growth uniformity is poor and batch preparation is difficult [28,29];

(2) Device consistency: Large variation between devices/cycles, poor adaptability of simulation calculations [29];

(3) Integration and stability: Process compatibility, packaging reliability, and biocompatibility need to be improved [28,33].

8.2. Future directions

The future directions are as follows:

(1) Wafer-level controllable synthesis and roll-to-roll mass production technology;
(2) Three-dimensional heterogeneous integrated neuromorphic chip;
(3) In-object computing and closed-loop adaptive systems;
(4) Multi-modal fusion sensing and establishment of market standards [14,30].

9. Conclusion

Two-dimensional materials provide material-level solutions for the integration of “sensing–storage–computing” owing to their unique properties, including flexibility, piezoelectricity, and phase-change characteristics. Materials such as graphene, MoS_2, VO_2, and van der Waals heterostructures enable the multifunctional integration of sensing, energy storage, and computing, while the collaborative design of “structure–material–algorithm” promotes the evolution of systems from functional separation toward integrated architectures. These devices demonstrate broad application prospects in wearable electronics, human-computer interaction, and environmental monitoring. With further breakthroughs in scalability, consistency, and system integration, two-dimensional material-based devices are expected to strongly support the development of next-generation intelligent sensing systems.

Disclosure statement

The authors declare no conflict of interest.

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