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Controlled Deposition Preparation of Low-Dimensional Nanomaterials and Their Applications in Optoelectronic Devices

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Abstract. Owing to the quantum confinement effect induced by dimensional confinement, significantly enhanced light-matter interaction, and excellent carrier transport properties, low-dimensional nanomaterials exhibit tremendous application potential in the field of next-generation optoelectronic devices. As a key link enabling the transition of low-dimensional nanomaterials from laboratory research to device applications, controlled deposition preparation techniques directly determine the morphology, layer count, crystal orientation, and defect density of materials, thereby profoundly affecting the optoelectronic performance and reliability of devices. This paper systematically reviews the main controlled deposition preparation techniques for low-dimensional nanomaterials, including the fundamental principles and research progress of chemical vapor deposition, physical vapor deposition, molecular beam epitaxy, and liquid-phase deposition. On this basis, it focuses on the typical applications and performance advantages of low-dimensional nanomaterials in optoelectronic devices such as photodetectors, solar cells, and light-emitting diodes. Finally, it deeply analyzes the main problems and challenges currently faced by this field from the aspects of uniformity and repeatability of material preparation, process compatibility of device integration, and cost and reliability of large-scale production, and prospects future research directions.

Keywords: low-dimensional nanomaterials, controlled deposition, chemical vapor deposition, optoelectronic devices, two-dimensional materials

1. Introduction

With advancements in microelectronics and optoelectronic technologies, traditional bulk semiconductor materials are reaching limitations in miniaturization, integration, and functional diversification. Low-dimensional nanomaterials display electronic structures and optical characteristics that are entirely distinct from those of bulk materials. The quantum confinement effect enables the bandgap of low-dimensional nanomaterials to be tuned by size and layer number, and their ultra-high specific surface area provides abundant degrees of freedom for surface engineering and heterostructure construction. These characteristics make them attract extensive attention in the optoelectronic field [1]. Among numerous preparation strategies for low-dimensional

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nanomaterials, controlled deposition technology is regarded as the core bridge connecting material synthesis and device manufacturing, as it can achieve localized growth and morphology control of materials directly on the substrate surface. Gas-phase deposition technologies represented by chemical vapor deposition (CVD) have successfully realized wafer-scale preparation of two-dimensional materials such as graphene and transition metal dichalcogenides (TMDs) [2]. However, how to precisely control the layer uniformity, crystal orientation consistency, and defect density of materials over a large area remains a key challenge restricting the practical application of low-dimensional nanomaterials.

This paper focuses on the controlled deposition preparation of low-dimensional nanomaterials and their applications in optoelectronic devices. It provides a theoretical basis and guidance for the performance improvement and industrial promotion of next-generation optoelectronic devices.

2. Controlled deposition preparation techniques for low-dimensional nanomaterials

2.1. Chemical vapor deposition

Chemical vapor deposition is currently one of the most widely used techniques for preparing low-dimensional nanomaterials. Its basic principle is to introduce gaseous precursors containing target elements into a reaction chamber, where the precursors undergo adsorption, decomposition, and chemical reactions on the substrate surface under specific temperature and pressure conditions, ultimately depositing to form the target material. The core advantage is that it can achieve precise control over material nucleation density, growth rate, and morphology by adjusting parameters such as growth temperature, precursor concentration, carrier gas flow rate, and chamber pressure [2].

CVD has achieved large-area single-layer graphene growth on metal catalytic substrates such as copper and nickel. Plasma-enhanced chemical vapor deposition (PECVD), by introducing plasma to reduce the reaction activation energy, can directly synthesize graphene on insulating substrate surfaces, avoiding damage and contamination caused by transfer processes. The synergistic regulation of hydrogen concentration and growth temperature can directly affect the nucleation and growth mode of graphene [2]. For two-dimensional materials like TMDs, CVD employs metal oxides and chalcogen precursors with a two-step heating process; for example, controlling the temperature at 700 °C inhibits MoS2 nucleation on graphene, promoting lateral growth for heterostructure formation [3]. Metal-organic chemical vapor deposition (MOCVD), which uses metal-organic precursors, can control supply uniformity more precisely and has realized orientation-controlled van der Waals epitaxial growth of MoSe2 monolayers [1].

2.2. Physical vapor deposition and molecular beam epitaxy

Physical vapor deposition (PVD) is another important category of low-dimensional nanomaterial preparation techniques, mainly including thermal evaporation, electron beam evaporation, and magnetron sputtering. Its basic principle is to vaporize the target material by physical means, and gas-phase atoms or molecules deposit on the substrate surface to form a thin film. Compared with CVD, the PVD process does not involve chemical reactions, and has the advantages of controllable composition, few impurities, and fast deposition rate, making it suitable for the preparation of metal, oxide, and some compound semiconductor nanofilm [4].

Molecular beam epitaxy (MBE) is a high-precision PVD technology under ultra-high vacuum environment. It achieves layer-by-layer epitaxial growth at the atomic level by controlling the beam intensity of each component atomic beam and the substrate temperature. MBE features high growth

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control accuracy and in-situ characterization capability, and can prepare low-dimensional semiconductor heterostructures with steep interfaces and extremely low defects, which is of prominent value in basic research. However, it requires expensive equipment and has a slow growth rate, making it difficult to meet the demand of large-scale industrialization [4].

2.3. Liquid-phase deposition and other preparation techniques

Liquid-phase deposition can be operated at atmospheric pressure and low temperature, with a simple process and low cost. Common approaches include the hydrothermal synthesis, spin coating, and electrophoretic deposition, which have been widely used for the preparation of large-area MoS2 thin films and PbSe nanoparticle photodetector films [4, 5]. However, liquid-phase products have low crystallinity, poor layer uniformity, and easily residual organic ligands on the surface, which will reduce the carrier mobility and optical performance of materials and limit their application in high-performance devices. The emerging microzone femtosecond laser deposition technology can realize localized in-situ deposition of heterodimensional heterostructures, providing a new path for controlled preparation [3].

3. Applications of low-dimensional nanomaterials in optoelectronic devices

3.1. Photodetectors

Photodetectors utilizing low-dimensional nanomaterials demonstrate significant advantages over traditional bulk semiconductors, including enhanced light absorption, broader spectral response, and quicker carrier transit times, leading to high-sensitivity and high-speed photodetection. For instance, single-layer MoS2, MoSe2, WS2 and other materials can absorb 5%–10% of incident sunlight even with a thickness of less than 1 nanometer, and their light absorption efficiency is one order of magnitude higher than that of traditional semiconductors such as GaAs and Si [6].

Photodetectors based on two-dimensional materials mainly include two working mechanisms: photoconductive and photovoltaic. Photoconductive devices use the conductance modulation of photogenerated carriers in the channel to realize optical signal detection, and usually have high optical gain and responsivity. Photovoltaic devices, based on the built-in electric field of p-n junctions or Schottky junctions, realize spontaneous separation of photogenerated carriers, featuring self-driven operation, low power consumption, and fast response [7]. Recent advancements include van der Waals heterostructures For example, MXene/two-dimensional material heterostructure photodetectors achieved a responsivity of 681.6 mA/W and a specific detectivity of 7.65×10^{13} Jones at a wavelength of 360 nm under zero bias, and still maintained about 90% of the initial response after 12 months [8]. Nitrogen-doped three-dimensional graphene-based detectors realized self-powered detection in the 1550 nm near-infrared band with a responsivity of 79.6 A/W, showcasing their applicability in light-controlled logic circuits and high-resolution imaging [7].

3.2. Solar cells and photovoltaic devices

The application of low-dimensional nanomaterials in solar cells and photovoltaic devices is mainly based on their tunable bandgap, high absorption coefficient, and solution processability. Two-dimensional TMD materials can be used as charge separation interfaces in photovoltaic devices by forming Schottky junctions or p-n junctions. Due to the atomic-level thickness and flexible characteristics of two-dimensional materials, photovoltaic devices based on two-dimensional

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materials have unique advantages such as ultra-thin, lightweight, and semi-transparent, showing application potential in portable electronic devices and building-integrated photovoltaics [9].

Perovskite materials are another research hotspot of low-dimensional nanomaterials in the photovoltaic field. Two-dimensional organic-inorganic hybrid perovskites significantly improve the environmental stability and ion migration inhibition ability of materials by introducing organic spacer cations. Studies have shown that the synergistic application of organic ligand regulation and heterostructure design is the core path to simultaneously improve the stability and efficiency of two-dimensional perovskite optoelectronic devices [10]. In addition, low-dimensional perovskite nanostructures, such as zero-dimensional quantum dots, one-dimensional nanowires and nanorods, have also received extensive attention in emerging fields such as neuromorphic vision computing due to their remarkable ion migration kinetics and tunable optoelectronic properties [11]. However, the photoelectric conversion efficiency of two-dimensional material-based solar cells is still much lower than that of traditional silicon-based and perovskite solar cells. How to achieve efficient light capture and charge collection while maintaining ultra-thin characteristics is a key problem to be solved urgently in this field.

3.3. Light-emitting diodes and novel optoelectronic devices

The application of low-dimensional nanomaterials in the field of light-emitting diodes (LEDs) mainly focuses on two-dimensional TMDs and low-dimensional perovskite materials. Single-layer TMDs, due to their direct bandgap characteristics and strong exciton effects, can achieve efficient photoluminescence and electroluminescence, and are ideal materials for preparing ultra-thin and flexible LEDs. The exciton-polariton effect generated by strong light-matter interaction in two-dimensional materials provides a new physical mechanism for realizing ultra-low threshold lasers and high-brightness light-emitting devices [6].

Low-dimensional perovskite LEDs are one of the most rapidly developing research directions in recent years. Perovskite quantum wires and nanorods exhibit excellent color purity and tunable emission wavelength in light-emitting devices due to their one-dimensional quantum confinement effect and enhanced radiative recombination rate. Studies have shown that when the diameter of perovskite nanowires decreases from about 100 nanometers to the quantum scale of several nanometers, the quantum confinement effect is significantly enhanced, and the luminescence performance undergoes a qualitative change [12]. Deterministic assembly of layered halide perovskite nanowire heterostructures has been achieved using free-form technology guided by femtoliter precursor solution meniscus, enabling new pathways for multi-dimensional integrated light-emitting devices [13].

Besides, low-dimensional nanomaterials also show broad prospects in novel devices such as optoelectronic artificial synapses, memristors, and neuromorphic computing. Optoelectronic devices based on low-dimensional nanomaterials can simulate the plasticity of biological synapses and neuronal behavior, realize the integration of optical signal sensing, storage, and computing, and provide a new hardware foundation for next-generation intelligent sensing systems [11].

4. Existing problems and challenges

Although controlled deposition techniques for low-dimensional nanomaterials have made remarkable progress, there are still bottlenecks in material quality and controllability. First of all, insufficient large-area uniformity and small single-crystal domain size are core problems. TMD films grown by CVD are mostly formed by splicing micron-sized small domains, and grain

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boundaries will reduce carrier mobility and increase device noise. Meanwhile, a high density of point defects such as chalcogen vacancies will damage the optoelectronic performance of materials as scattering and recombination centers [14]. Second, the precise control and repeatability of the CVD growth process need to be improved. The growth of two-dimensional compounds involves the transport and reaction of multiple precursors, which is highly sensitive to parameters such as temperature, gas flow, and pressure, easily leading to differences in layer number and performance of samples from different batches [15]. At present, only a few materials such as graphene and MoS2 have realized wafer-scale single-crystal growth, and strategies to enlarge single-crystal domains are usually accompanied by problems such as decreased growth rate and increased cost, making it difficult to balance quality and efficiency [16]. In addition, material damage caused by transfer processes cannot be ignored. Two-dimensional materials grown on metal substrates need to be transferred to target substrates, and defects such as breakage, wrinkles, and contamination are easily introduced during the process [17].

At the device level, low-dimensional nanomaterial optoelectronic devices face the dual challenges of performance optimization and process integration. In terms of performance, high responsivity and high detectivity under laboratory conditions often rely on specific structures and test environments, and the stability and reliability in practical applications still need to be verified. For example, high-gain photoconductive detectors have slow response speed, making it difficult to adapt to high-speed optical communication and imaging scenarios, photovoltaic devices have fast response speed but generally lower responsivity and optical gain [7]. In terms of integration, the compatibility of low-dimensional nanomaterials with silicon-based CMOS technology is the core obstacle. The CVD growth temperature of two-dimensional materials is usually 600–1000 °C, far exceeding the temperature budget of back-end-of-line interconnection processes, making monolithic integration difficult. Meanwhile, processes such as material patterning and electrode contact are still immature, and problems such as contact resistance and Fermi level pinning significantly affect device performance. Moreover, atomic-thick materials are extremely sensitive to surface defects and interface contamination, and it is difficult to fully retain their intrinsic properties during the preparation process [14].

From the perspective of industrialization, large-scale production still faces multiple obstacles such as cost, yield, and lack of standards. High-precision technologies such as MBE have expensive equipment and limited production capacity. The process cost of large-area uniform growth is comparatively costly, notwithstanding CVD's potential for scaling up. It is challenging to adapt liquid-phase technologies to high-performance devices due to their low cost and inadequate product quality [4]. The device performance discreteness is significantly higher than that of traditional semiconductor devices, and materials such as black phosphorus and some perovskites are easily oxidized and degraded in air, resulting in insufficient long-term stability. Immature packaging technology also limits commercialization progress [10]. In addition, the industry has not yet formed unified performance test standards and reliability evaluation specifications, which also restricts the standardized development of the industry.

5. Conclusions

This paper systematically reviews the controlled deposition preparation techniques of low-dimensional nanomaterials and their application progress in optoelectronic devices. In terms of preparation techniques, chemical vapor deposition has become the mainstream preparation method for two-dimensional materials such as graphene and TMDs by virtue of its parameter tunability and large-area growth capability. Physical vapor deposition and molecular beam epitaxy have unique

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advantages in the preparation of high-precision thin films and heterostructures. Liquid-phase deposition and emerging laser deposition technologies provide new paths for low-cost, patterned, and heterodimensional structure preparation. In terms of applications, low-dimensional nanomaterials all exhibit excellent performance and broad application prospects in the fields of photodetectors, solar cells, light-emitting diodes, and neuromorphic optoelectronic devices. Among them, high-performance photodetectors based on two-dimensional material heterostructures and low-dimensional perovskite light-emitting devices are currently the most active research directions.

However, the field still faces many challenges. At the material preparation level, problems such as insufficient large-area uniformity, high defect density, poor growth repeatability, and transfer damage restrict the further improvement of material quality. At the device level, the trade-off between performance and speed, compatibility with CMOS processes, and integration problems such as contact resistance urgently need to be broken through. At the industrialization level, obstacles such as high cost, low yield, insufficient stability, and lack of standards limit the commercialization process.

Future research can focus on the following directions: First, develop low-temperature, transfer-free direct growth technologies to realize in-situ high-quality deposition of two-dimensional materials on target substrates. Second, precisely regulate the band structure and carrier dynamics of low-dimensional nanomaterials through defect engineering and interface engineering to further improve device performance. Third, develop device integration solutions compatible with CMOS processes to promote the evolution of low-dimensional nanomaterial optoelectronic devices from laboratory prototypes to practical systems. Fourth, establish unified performance testing and reliability evaluation standards to provide technical support for industrialization development. With the continuous progress of preparation techniques and in-depth understanding of device physics, low-dimensional nanomaterials are expected to play an increasingly important role in next-generation optoelectronic technologies.

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