

Two-Dimensional Nanomaterials as Technology Marvels



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Abstract Two-dimensional (2D) nanomaterials have emerged as a new class of materials with unique properties and potential applications in various fields, such as electronics, energy, and medicine. This chapter provides precisely an overview of the synthesis, properties, and applications of 2D nanomaterials, including graphene, transition metal dichalcogenides, and black phosphorus. We begin by discussing the each of these 2D materials, their methods to synthesize, such as mechanical exfoliation, chemical vapor deposition, and liquid-phase exfoliation etc. Next, we describe their remarkable properties, such as high electrical conductivity, large surface area, and tunable bandgap that make them suitable for diverse applications. We then explore their various applications, including in flexible electronics, energy storage and conversion, sensing, and biomedicine inside each material description. Moreover, we highlight some of the challenges and limitations that need to be addressed for their commercialization and large-scale production. Finally, the chapter concludes with a summary of the current state of research and suggests possible directions for future work in this exciting field.

Keywords 2D materials · MXenes · Graphene · Metal–organic framework · Nanosheets · Nanoparticles

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1 Introduction

Two-dimensional (2D) nanomaterials are a class of materials that have a thickness of only a few atomic or molecular layers, while their other two dimensions extend to macroscopic scales. These materials are also known as 2D materials, ultrathin materials, or nanosheets. Two-dimensional (2D) nanomaterials are a class of materials that are characterized by their ultrathin and flat nature, with thicknesses typically measured in the nanometer scale [1, 2]. They possess unique physical, chemical, and mechanical properties that differ from their bulk counterparts, making them highly attractive for a wide range of applications in various fields such as electronics, optoelectronics, catalysis, energy, and biomedicine [3]. Graphene, a single layer of carbon atoms arranged in a honeycomb lattice, is the most well-known 2D material [3, 4]. However, there are many other 2D materials, including transition metal dichalcogenides (TMDs) such as molybdenum disulfide (MoS_2), boron nitride (BN), and black phosphorus (BP), among others. 2D materials have unique physical and chemical properties compared to their bulk counterparts. Due to their large surface area to volume ratio, they exhibit enhanced surface reactivity and catalytic activity. In addition, they have high mechanical strength and flexibility, which makes them attractive for use in electronic and optoelectronic devices, as well as in nanocomposites and energy storage applications [5].

One of the most promising applications of 2D materials is in electronics, where they can be used to create faster, more efficient, and more compact devices. For example, graphene is an excellent conductor of electricity and has been used to make high-speed transistors and flexible, transparent conductive films. TMDs, on the other hand, have a bandgap, which allows them to be used in optoelectronic devices such as photodetectors and solar cells. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, is the most well-known 2D nanomaterial. However, over the past decade, there has been a rapid development of new 2D materials, including transition metal dichalcogenides (TMDs), boron nitride (BN), black phosphorus (BP), and many others as shown in Fig. 1a and b.

TMDs, such as MoS_2 and WSe_2 , are composed of a transition metal layer sandwiched between two chalcogenide layers. They exhibit excellent electronic and optical properties, making them promising for applications in transistors, photodetectors, and solar cells. BN, which has a similar structure to graphene, consists of boron and nitrogen atoms arranged in a hexagonal lattice. It possesses high thermal and chemical stability, making it an ideal insulator for electronics and photonics applications. BP, which consists of a single layer of phosphorus atoms arranged in a puckered honeycomb lattice, has attracted much attention due to its excellent electronic and optoelectronic properties. It has been explored for applications in solar cells, sensors, and transistors. Other 2D materials that have been extensively studied include transition metal carbides and nitrides (MXenes), metal–organic frameworks (MOFs), and perovskites. Overall, 2D nanomaterials offer tremendous potential for a variety of applications due to their unique properties, and their further development and exploration is an active area of research in materials science and engineering.

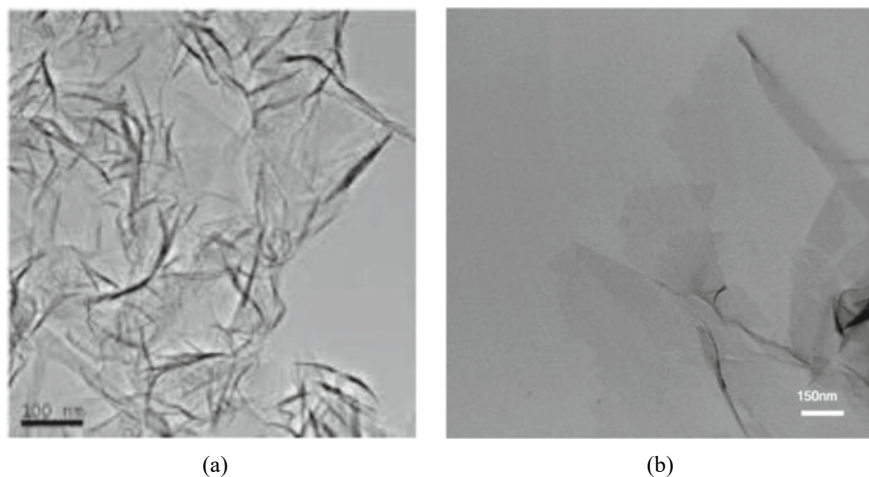


Fig. 1 Transmission electron microscopic images of **a** crumpled grapheme and **b** two relatively large centrally overlapped BNNSs [6]

2 Silicene

Silicene is a 2D material that consists of a single layer of silicon atoms arranged in a honeycomb lattice, similar to graphene. It was first proposed theoretically in 1994, but it was not until 2010 that researchers were able to synthesize it for the first time, using a silver substrate to stabilize the silicon atoms. Silicene is a 2D allotrope of silicon, which is composed of a single layer of silicon atoms arranged in a honeycomb lattice. It is analogous to graphene, which is composed of a single layer of carbon atoms arranged in a similar lattice. Silicene was first predicted to exist in 1994 by Takeda and Shiraishi, but it was not until 2010 that it was successfully synthesized by researchers in Germany [7, 8].

Silicene has a number of unique properties that make it highly attractive for potential applications. Like graphene, it is highly flexible, strong, and lightweight, and it exhibits excellent electrical conductivity. However, unlike graphene, silicene is a semiconductor, with a bandgap that can be tuned by controlling the size and shape of the lattice. Silicene has a number of unique physical and electronic properties, including high electron mobility, a tunable bandgap, and strong spin-orbit coupling. These properties make it a promising candidate for use in electronics and optoelectronics applications. Unlike graphene, silicene has a buckled structure, which gives it a distinct electronic structure with two different types of silicon atoms [9].

Figure 2 reveals the energy-crystal wave vector ($E-k$) dispersion of silicene. Silicene can be synthesized by a number of methods, including molecular beam epitaxy (MBE) and chemical vapor deposition (CVD). In MBE, silicon atoms are deposited onto a substrate in a high vacuum environment, where they arrange themselves into a silicene lattice. In CVD, silicon-containing gases are passed over a

substrate at high temperatures, where they react to form a silicene layer. Silicene has been proposed for a range of potential applications, including in electronics, optoelectronics, and energy storage. For example, silicene-based transistors could potentially offer better performance than traditional silicon-based transistors due to their superior electron mobility. Additionally, silicene could be used as a catalyst for various chemical reactions due to its high surface area and reactivity. Silicene has potential applications in a variety of fields, including electronics, optoelectronics, and energy storage. It could be used to create more efficient transistors and sensors, as well as to create new types of solar cells and batteries. Its unique properties also make it a promising candidate for use in quantum computing.

However, there are also several challenges that need to be addressed before silicene can be widely used in practical applications. One major issue is the difficulty of synthesizing and stabilizing silicene in a controlled manner, since it is highly reactive and tends to form clusters or even revert back to bulk silicon. Another challenge is the lack of large-area, high-quality silicene samples, which limits the ability to study its properties and develop practical devices. One of the main challenges in the use of silicene is its stability. Unlike graphene, which is stable under normal conditions, silicene is highly reactive and can easily oxidize in air. This limits its potential use in practical applications, and researchers are working to develop methods to stabilize it. In addition, the synthesis of silicene is still a challenging process, and further research is needed to develop more efficient and scalable methods of synthesis. In conclusion, silicene is a promising 2D material with unique electronic and physical properties that make it attractive for a range of applications. While there are still challenges to be addressed in its synthesis and stability, ongoing research is expected to yield new insights into its properties and potential uses [7–9, 11–31].

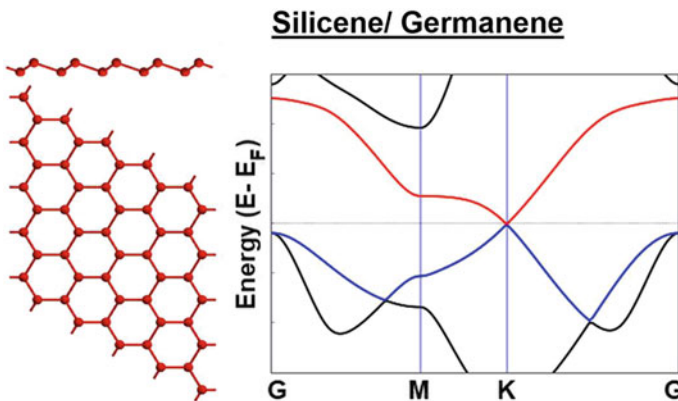


Fig. 2 ($5 \times 5 \times 1$ Supercell) of the monolayer silicene/germanene and its energy-crystal wave vector (E - k) dispersion [10]

3 MXenes

MXenes are a family of two-dimensional materials that are composed of transition metal carbides, nitrides, and carbonitrides. MXenes were first discovered in 2011 by researchers at Drexel University in Philadelphia, who were studying the synthesis of MAX phases. MAX phases are ternary compounds that are composed of a transition metal, a group A element, and carbon or nitrogen. MXenes are produced by selectively etching the A element layer from the MAX phase, leaving behind a layered two-dimensional structure. MXenes are a relatively new class of 2D materials that have attracted a lot of attention due to their unique properties and potential applications in a variety of fields. MXenes are transition metal carbides or nitrides that are produced by selectively etching the A layers of MAX phases, which are layered materials composed of a transition metal (M), a Group IIIA or IVA element (A), and carbon and/or nitrogen (X) arranged in a layered structure. MXenes have a number of unique properties that make them attractive for various applications. For example, they have high electrical conductivity, high surface area, and excellent mechanical properties.

MXenes are also hydrophilic, meaning they can be dispersed in water, making them easy to process. MXenes have a number of unique properties that make them promising candidates for a wide range of applications, including high electrical conductivity, high mechanical strength, and excellent thermal stability. They also exhibit tunable surface chemistry, which can be modified by changing the nature of the A element or by functionalizing the surface with organic or inorganic molecules. MXenes can be synthesized by a two-step process that involves etching the A layers of a MAX phase using a strong acid, followed by washing and delaminating the resulting material to produce MXene sheets. There are many different types of MXenes, each with unique properties, depending on the transition metal, the A layer element, and the etching conditions used in the synthesis. MXenes can be synthesized using a variety of methods, including chemical etching, electrochemical etching, and hydrothermal synthesis shown in Fig. 3. The most common method is chemical etching, which involves the use of strong acids such as hydrofluoric acid (HF) or hydrochloric acid (HCl) to selectively remove the A element layer from the MAX phase. Electrochemical etching involves using an electrical current to selectively etch the A element layer, while hydrothermal synthesis involves the use of high temperatures and pressures to synthesize MXenes from precursors.

MXenes have potential applications in a wide range of fields, including energy storage, catalysis, and sensors. In energy storage, MXenes have been explored as anode materials for lithium-ion batteries, as well as for supercapacitors, due to their high conductivity and high surface area. In catalysis, MXenes have been shown to have excellent activity for a variety of reactions, including hydrogen evolution and oxygen reduction. In sensors, MXenes have been used for gas sensing and biosensing applications, due to their high surface area and ease of functionalization. MXenes

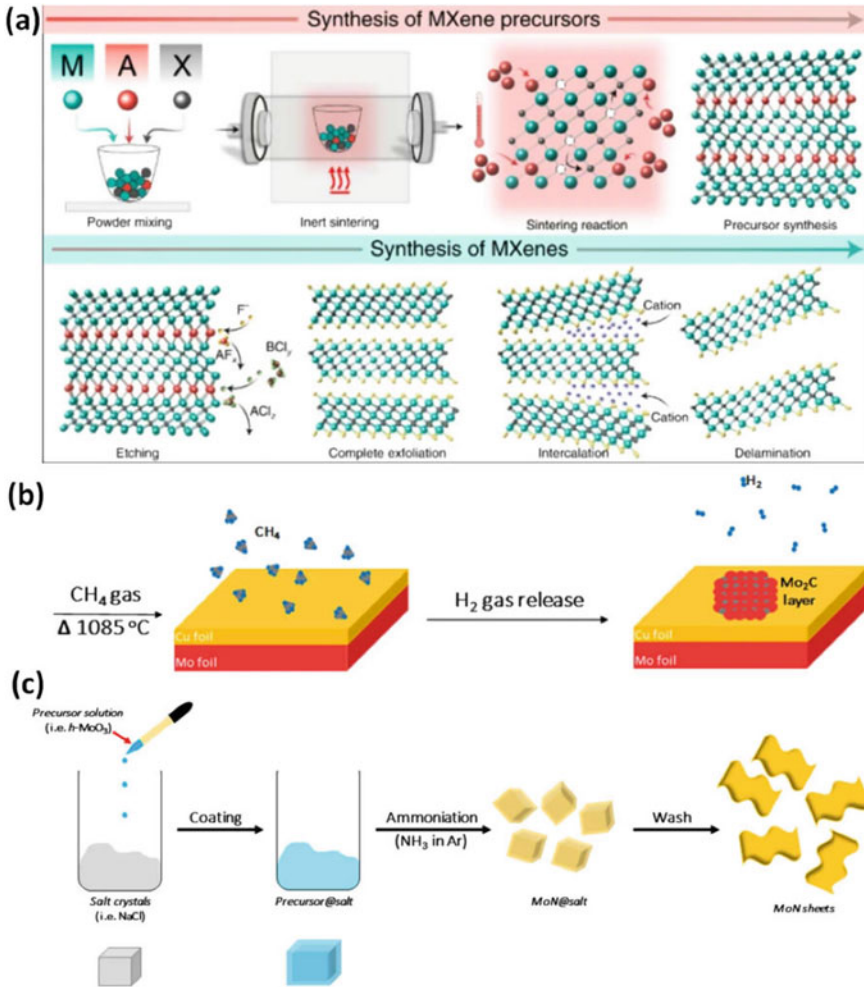


Fig. 3 Steps in the synthesis of MXene nanomaterials by top-down method from precursor to etching; bottom-up techniques are shown schematically in **b** [32]

have potential applications in a wide range of fields, including energy storage, catalysis, sensors, and electronics. They have been studied as electrode materials for supercapacitors and batteries due to their high electrical conductivity and large surface area. MXenes have also been explored as catalysts for hydrogen evolution reactions and as sensors for the detection of gases and biomolecules. Their high mechanical strength and thermal stability make them promising candidates for use in electronic devices such as flexible displays and touch screens.

One of the main challenges in the use of MXenes is their tendency to oxidize in air, which can affect their properties and limit their stability. Researchers are working to

develop methods to stabilize MXenes and improve their performance under ambient conditions. In addition, the synthesis of MXenes can be a complex process, and there is a need for further research to develop more efficient and scalable methods of synthesis. One of the main challenges in the use of MXenes is their stability. MXenes are highly reactive and can easily oxidize in air, which can limit their potential use in practical applications. Researchers are working to develop methods to stabilize MXenes, such as by using protective coatings or by functionalizing the surface with molecules that can inhibit oxidation. In addition, the synthesis of MXenes is still a challenging process, and further research is needed to develop more efficient and scalable methods of synthesis. In conclusion, MXenes are a promising class of 2D materials with unique properties and potential applications in a wide range of fields. While there are still challenges to be addressed in their synthesis and stability, ongoing research is expected to yield new insights into their properties and potential uses. In conclusion, MXenes are a promising class of 2D materials that offer a wide range of properties and potential applications. While there are still challenges to be addressed in their synthesis and stability, ongoing research is expected to yield new insights into their properties and potential uses [33–51].

4 2D Metal–Organic Framework Nanosheets (2D MOFs)

Two-dimensional metal–organic framework (MOF) nanosheets are a class of crystalline materials composed of metal ions or clusters coordinated to organic ligands. They have a layered structure, with a thickness of only a few nanometers, and can be synthesized through a variety of methods. Two-dimensional (2D) metal–organic framework (MOF) nanosheets are a type of 2D nanomaterial composed of metal ions or clusters linked by organic ligands. MOFs are typically three-dimensional materials, but the use of specific ligands and metal ions can result in the formation of 2D MOF nanosheets.

2D MOF nanosheets have a number of unique properties, including high surface area, tunable porosity, and catalytic activity. They can be functionalized with a variety of functional groups, making them versatile materials for a range of applications. The porosity of MOFs allows for the incorporation of guest molecules within the structure, making them ideal for gas separation, storage, and sensing applications. 2D MOF nanosheets have a number of unique properties, including a high surface area, porosity, and tunable chemical and electronic properties. The porosity of these materials makes them attractive for applications such as gas storage and separation, catalysis, and sensing. Their tunable properties make them attractive for applications such as electronic and optical devices.

2D MOF nanosheets can be synthesized through a variety of methods, including solvent-assisted exfoliation, surfactant-assisted exfoliation, and liquid-phase exfoliation as shown in Fig. 4a–d. In solvent-assisted exfoliation, MOFs are dispersed in a solvent, and sonication is used to exfoliate the material into nanosheets. Surfactant-assisted exfoliation involves the use of surfactants to stabilize the nanosheets in

a solvent. Liquid-phase exfoliation is a more recent method that involves the use of high-pressure homogenization to exfoliate the MOFs in a liquid medium. 2D MOF nanosheets can be synthesized using a variety of methods, including solvothermal synthesis, liquid-phase exfoliation, and chemical vapor deposition (CVD). In solvothermal synthesis, metal ions or clusters and organic ligands are combined in a solvent and heated under high pressure to form 2D MOF nanosheets. In liquid-phase exfoliation, bulk MOF crystals are dispersed in a solvent and sonicated to produce 2D nanosheets. CVD involves the deposition of metal and organic precursors onto a substrate, followed by thermal treatment to form a 2D MOF nanosheet.

2D MOF nanosheets have a wide range of applications in areas such as gas storage, catalysis, and sensing. Due to their high surface area and tunable porosity, they can be used as efficient adsorbents for the separation and storage of gases such as CO_2 and H_2 . They have also been studied as catalysts for various chemical reactions, including the reduction of CO_2 to produce valuable chemicals such as methanol. In addition, their unique properties make them promising candidates for use in electronic and photonic devices. 2D MOF nanosheets have potential applications in a wide range of fields, including gas storage and separation, catalysis, sensing, and electronics. Their high surface area and porosity make them attractive for use in gas storage and separation applications, such as carbon capture and storage. They also have potential as catalysts for chemical reactions, due to their tunable chemical properties. 2D MOF nanosheets have also been explored as sensors for the detection of gases and biomolecules, and as electronic devices such as field-effect transistors.

One of the main challenges in the use of 2D MOF nanosheets is their stability. MOFs are sensitive to moisture and can degrade over time, which can limit their

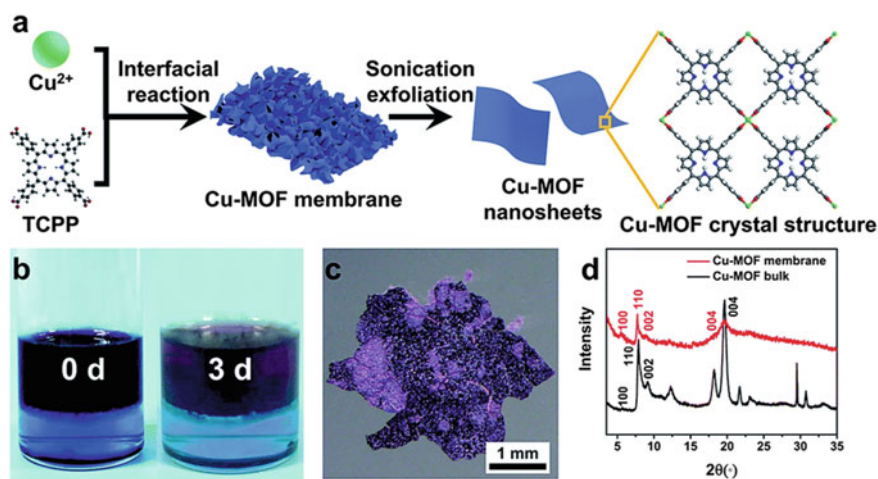


Fig. 4 **a** Synthetic procedure and crystal structure of Cu-MOF nanosheets (schematic). **b** Photographs of the color changes of two immiscible phases before and after the reaction. **c** Optical image of a Cu-MOF membrane. **d** PXRD spectra of a Cu-MOF membrane and Cu-MOF bulk counterparts [52]

potential use in practical applications. Researchers are working to develop methods to stabilize MOFs, such as by using protective coatings or by modifying the structure of the material. In addition, the synthesis of MOF nanosheets is still a challenging process, and further research is needed to develop more efficient and scalable methods of synthesis. One of the main challenges in the use of 2D MOF nanosheets is their stability. Like other 2D materials, they can be prone to oxidation and degradation in air and water. Researchers are working to develop methods to stabilize 2D MOF nanosheets, such as by using protective coatings or by functionalizing the surface with molecules that can inhibit degradation. In addition, the synthesis of 2D MOF nanosheets is still a challenging process, and further research is needed to develop more efficient and scalable methods of synthesis. 2D MOF nanosheets are a promising class of materials with a wide range of properties and potential applications. While there are still challenges to be addressed in their stability and synthesis, ongoing research is expected to yield new insights into their properties and potential uses. In conclusion, 2D MOF nanosheets are a promising class of 2D materials with unique properties and potential applications in a wide range of fields. While there are still challenges to be addressed in their stability and synthesis, ongoing research is expected to yield new insights into their properties and potential uses [53–57].

5 Metal Nanostructured Materials

Metal-based nanomaterials have gained attention for various applications due to their promising properties [58, 59]. One important area of research is the development of nanoscale catalysts, which exhibit exceptional catalytic activity and offer more efficient and effective reactions. At the nanoscale level, these materials have a large surface area, numerous binding sites, and favorable thermodynamics and kinetics for heterogeneous reactions [60], making them highly desirable for catalysis. They are also being explored for creating artificial enzymes [61]. Researchers are now focusing on designing specific nano-architectures to improve their performance. There are several synthesis methods available for creating these materials, including hydrothermal, solvothermal, sol–gel, electroless, electrochemical, and physical methods.

Due to the growing demand for alternative, clean, and renewable energy sources, metal-based nanostructured materials are being extensively studied for the production of robust electrodes that can be used in water splitting, batteries, and solar cells [60]. Researchers are striving to improve the performance of existing lithium-ion batteries by improving their safety, lifetime, and size [62]. Nanostructured metal-oxide-based materials show promise as electrode materials for high-performance charge storage devices, and metal-based nanostructured electrodes are being evaluated for use as both anodes and cathodes to overcome the challenges of conventional electrodes [63].

6 Nanoparticles with Core–shell

Nanoparticles can be classified into three categories based on their composition: simple, composite, or core–shell. Simple nanoparticles are made up of a single material, while composite and core–shell nanoparticles consist of two or more materials. Core–shell nanoparticles consist of an inner material (the core) and an outer material (the shell). Different combinations of materials can be used to create core–shell nanoparticles, including organic/organic, inorganic/organic, inorganic/inorganic, and organic/inorganic materials [64].

Spherical core–shell nanoparticles are a practical way to introduce multiple functionalities on a nanoscopic scale [65]. The properties of the core and shell can be controlled by adjusting the ratio of the constituent materials, and their shape, size, and composition are critical factors in determining their properties. The shell material can improve the chemical and thermal stabilities of the core material, making it more durable [66]. The core–shell design is particularly useful when an inexpensive material is unstable or easily oxidizable. For example, magnetic nanoparticles are sensitive to air, acids, and bases, but coating them with organic or inorganic shells can protect them from degradation [67].

7 Conclusions

In conclusion, 2D nanomaterials have emerged as a fascinating area of research in nanoscience and nanotechnology due to their unique and extraordinary properties. Graphene, the first 2D material discovered, has opened up new possibilities for a wide range of applications in electronics, energy storage, and biomedicine. Other 2D materials such as transition metal dichalcogenides, black phosphorus, and boron nitride have also shown promise for various applications. The synthesis and functionalization of 2D nanomaterials have advanced significantly in recent years, enabling the development of new devices with improved performance. Although challenges such as scalability and commercial viability still exist, 2D nanomaterials hold tremendous potential for future technological advancements.

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