

Application of Two-Dimensional Semiconductor In Transistor

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Abstract. Two-dimensional semiconductor materials are a class of thin film materials with atomic thickness and unique electronic structure. They have important application prospects in semiconductor technology, especially in field effect transistors (FETs). This paper reviews the properties, applications, and challenges of two-dimensional semiconductor materials and their potential in different types of FETs. This paper introduces the representative members of two-dimensional semiconductor materials, including graphene, transition metal chalcogenides (TMDs) and black phosphorus, as well as their synthesis methods and bandgap regulation strategies. The paper then analyzes the applications and advantages of 2D semiconductor materials in digital, optoelectronic, pressure-sensitive, and brain-like FETs and their broad uses in electronic, optoelectronic, sensing, and energy storage devices. Finally, the main challenges facing 2D semiconductor materials in FETs are discussed, including material quality, contact resistance, process compatibility and environmental stability, and future research directions and prospects.

Keywords: Two-dimensional Semiconductor Materials, Field Effect Transistors, Band Gap Regulation, Photoelectric.

1. Introduction

The exploration and application of two-dimensional materials have brought great changes to the field of semiconductor technology. These materials have extraordinary physical and chemical properties and have good application prospects for advanced device structures, especially field effect transistors (FETs). Graphene was the first clear example of a two-dimensional semiconductor. Its unique lattice structure, excellent electron mobility, and impressive thermal stability make it a strong candidate for microelectronics applications. Transition metal sulfides (TMDs) such as MoS₂ are also promising two-dimensional materials. These materials have unique band structures and significant semiconductor properties, which are of great value for developing next-generation electronic devices. This paper will comprehensively discuss the properties of 2D semiconductor materials and their potential applications in various FETs, especially in digital FETs, photoelectric FETs, pressure sensors, and neuromorphic computing. Two-dimensional semiconductor materials bring new possibilities and solutions for FETs' design and performance optimization. However, the integration of two-dimensional semiconductor materials into FETs also faces many challenges, such as material synthesis, device preparation, and performance issues. Overcoming these obstacles is key to unlocking the enormous potential of two-dimensional semiconductor materials in a variety of FETs applications. This paper will comprehensively analyze this emerging field's current situation and development prospect and provide reference and inspiration for the research and application of related fields.

The structure of this paper is as follows: First, the definition and classification of 2D semiconductor materials and the differences and advantages from traditional 3D semiconductor materials are introduced. Secondly, the applications and advantages of 2D semiconductor materials in digital FETs, photoelectric FETs, pressure sensors and neuromorphic computing are introduced, as well as the related theoretical and experimental research progress. Then, the challenges and solutions of 2D semiconductor materials in FETs are analyzed, including aspects of material synthesis, contact resistance, process integration, and environmental stability.

2. Properties of two-dimensional semiconductor materials and their potential in transistors

With the exploration and application of two-dimensional (2D) materials, the field of semiconductor technology has recently undergone tremendous changes. These materials have extraordinary physical and chemical properties and have good application prospects for advanced device structures, especially field effect transistors (Fets).

Graphene represents the first well-documented instance of a two-dimensional semiconductor. Its unique lattice structure, excellent electron mobility and impressive thermal stability mark it as a promising candidate for microelectronics applications. A Hene semiconductor refers to a class of materials that introduce a band gap into the graphene material to make it have semiconductor properties. Graphene itself is a carbon material with a special structure, with excellent electron transport properties and thermal conductivity, but due to its zero band gap characteristics, its application in traditional semiconductor devices is limited.

Various methods have been tried to change the bandgap properties of graphene, the most common of which is achieved by chemical means. Chemical modifications can be made by covalent or non-covalent action. Covalent modifications usually destroy some properties of graphene conjugated systems, thereby changing its bandgap properties. Non-covalent modification methods, such as pi-pi stacking interactions, are thought to preserve graphene's natural structure and properties [1]. By introducing boron nitride (BN) domains into graphene, the band gap of graphene can be effectively opened. The alloying of graphene and BN can form a band gap and regulate the size of the band gap by regulating the concentration and size of the BN domain.

Transition metal disulfides (TMDs), including MoS₂, have emerged as a highly promising class of two-dimensional materials. These materials possess unique band structures and remarkable semiconductor properties, making them valuable for advancing next-generation electronic devices. An exciting example is the use of molybdenum disulfide in transparent thin film transistors (TFTs). These TFTs exhibit high mobility, enabling their application in both analog and digital memory computing systems. In particular, the incorporation of MoS₂ semiconductor channels in a two-gate two-dimensional TFT design offers a promising avenue for future digital and neuromorphic computing applications.

3. Application of two-dimensional semiconductor materials to more types of field-effect transistors (FETs)

Two-dimensional (2D) semiconductor materials are thin film materials composed of a single layer or a few layers of atoms, and they offer new opportunities and solutions for the design and performance optimization of field effect transistors (FETs). The principle of 2D semiconductor FET is shown in Figure 1. These semiconductors, including transition metal chalcogenides (such as MoS₂, WS₂) and phosphones (such as black phosphorus), have adjustable band gaps and excellent electrical properties, showing significant advantages in FET applications.

Many two-dimensional materials have been widely studied and applied to various types of FETs. For example, single - and multilayer MoS₂, whose band gap is controlled by their thickness, can manufacture high-performance FETs. The special properties of MoS₂ allow it to improve the switching speed of the FET while maintaining excellent conductivity and low energy consumption. In addition, black phosphorus is also a two-dimensional material of interest, and in some studies, black phosphorus FETs have shown excellent electrical transport properties and can maintain stability in the face of changes in ambient temperature and humidity. In addition, WS₂, WSe₂ and other disulfides, thanks to their unique band gap and electrical transport properties, are ideal for the manufacture of high-performance FETs.

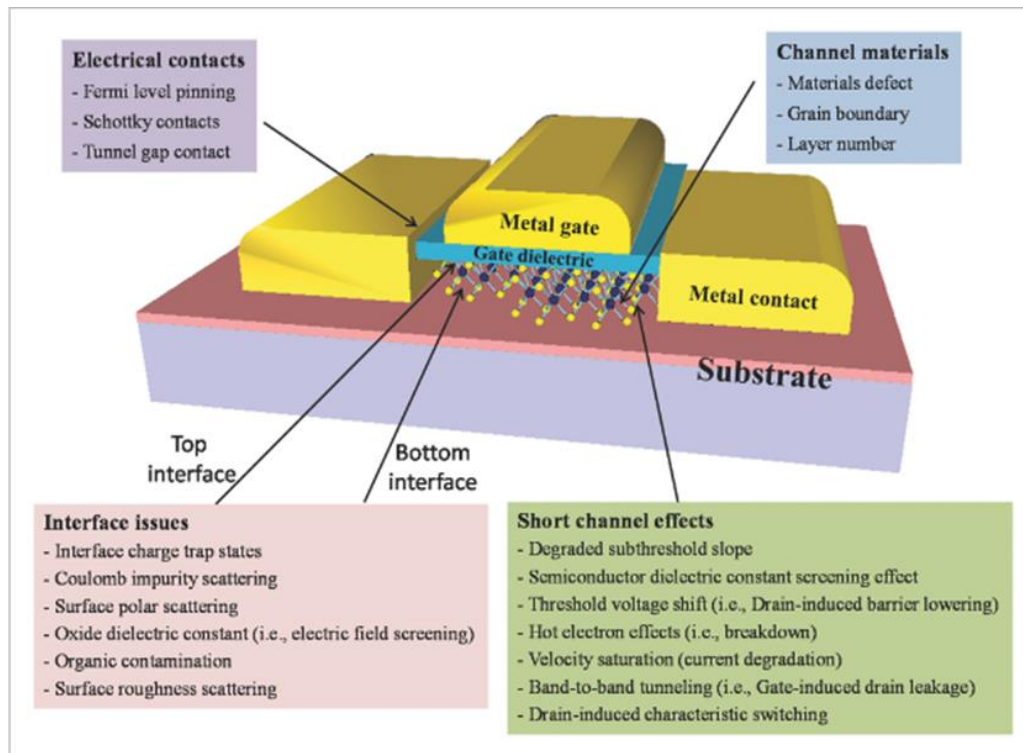


Fig 1. Schematic diagram of two-dimensional semiconductor FETs.

The figure shows the key factors that affect the performance of 2D devices, including channel materials, metal contact, 2D dielectric interfaces, and short channel effects [2].

3.1. FETs in modern electronics

Digital Field-Effect Transistors (FETs) play a crucial role in modern electronics, serving as the backbone for various devices, including microprocessors and memory chips. However, the emergence of two-dimensional (2D) semiconductor materials has introduced a new era, bringing with it a range of unique properties that traditional three-dimensional semiconductors cannot replicate. This has the potential to completely revolutionize the performance and capabilities of digital FETs, paving the way for groundbreaking advancements in electronic technology.

Thanks to the atomically thin conductive channels of two-dimensional semiconductors, these materials exhibit quantum mechanical behavior that can fundamentally change the performance of transistors. For example, thermal limitations limit conventional field-effect transistors (FETs) in their subthreshold swing. However, in two-dimensional Fets, the thin channel region allows tunn-based transistor operation, potentially resulting in subthermal subthreshold fluctuations and reduced energy consumption per operation. In addition, due to its ultra-thin nature, the two-dimensional material provides excellent electrostatic control in the channel area. This feature enables more aggressive device scaling beyond the expected limits of traditional semiconductors [3]. These advances are critical to continuing to push the boundaries of Moore's Law, which is essential for the continued development of digital field effectors and the semiconductor industry as a whole. The mobility of the carriers largely determines the performance of digital FETs, and here again the 2D material comes into play, outperforming the 3D material. Materials such as graphene can produce extremely high carrier mobility due to their zero effective mass of carriers, while transition metal disulfide compounds (TMDCs), such as MoS2 and WSe2, have considerable carrier mobility and considerable bandgap, conducive to low standby power and high-performance digital applications [2]. Short-channel effects in MoS2 FETs, as shown in Fig. 2. In addition, the diverse library of 2D materials and the ability to stack them on top of each other offers the promise that designers' digital FETs can be tailored to specific requirements. Atomically accurate layer engineering optimizes individual devices' performance and enables innovative device concepts such as negative-capacitance field-effect tubes and steep slope devices.

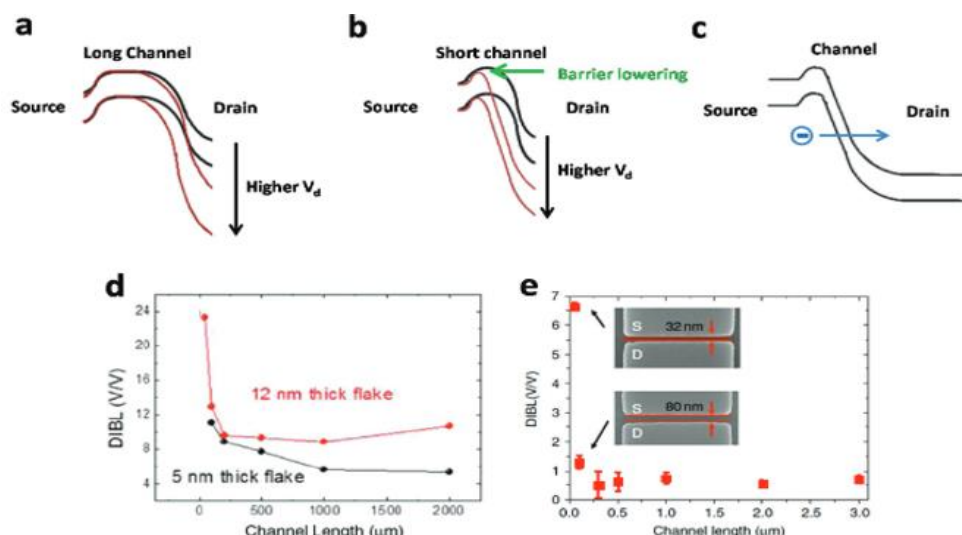


Fig 2. Short channel effect in MoS₂ FET [2].

a) Long channel field effect tube strip diagram with constant energy barrier on the source side. b) The band diagram of the short-channel FET shows a lower barrier height at a high drain bias (red) compared to a low drain bias (black). c) Band diagram of FET under large electric field, showing the idea of interband tunneling and GIDL (electron tunneling direction is blue). d) Influence of semiconductor (MoS₂) thickness on DIBL. e) DIBL in a single-layer MoS₂ field-effect tube using 34-60 nm HfO₂/AlO_x gate medium.

3.2. Photoelectric field effect transistor

Optoelectronic Field-Effect Transistors or simply, photo-FETs have a crucial role in converting light signals into electrical signals. They serve as foundational components in photodetectors, imaging sensors, fiber optic communication systems and more. With the advent of two-dimensional (2D) semiconductor materials, the design and functional characteristics of photo-FETs have found new potential for advancements. Performance comparison of various 2D materials-based photodetectors, as shown in Fig.3.

Herein, 2D semiconductor materials with direct bandgaps come into play as they possess inherent advantages for optoelectronic applications. The atomically thin nature of these 2D materials can provoke strong interaction with light, leading to high photo-responsivity. Moreover, their characteristic tunable bandgaps spanning a broad spectrum from the ultraviolet to the infrared region offers heightened flexibility in absorption and emission process, and consequently, improved device performance. MoS₂ serves as a representative example among the family of transition metal dichalcogenides (TMDCs) that are being extensively explored for optoelectronic FETs. A few prominent advantages of MoS₂-based photo-FETs include the high photosensitivity due to the direct bandgap in monolayers, fast photoresponse, and compatibility with diverse substrates due to its inherent mechanical flexibility. Besides, the gated control in FETs allows the device operation to be conveniently regulated, finely tuning the photoresponse [4].

Moreover, black phosphorus (BP) is a rising star among 2D semiconductors for photo-FETs. It offers a direct and widely tunable bandgap together with high carrier mobility. As a result, BP-based photo-FETs can deliver remarkable high photo-responsivity and fast response across a wide wavelength range. Interestingly, the field of photo-FETs with 2D materials goes beyond conventional single-layer configurations. VdW heterostructures, designed by vertically stacking different 2D materials, exhibit intriguing new properties due to the strong interlayer coupling. These engineered structures provide unprecedented opportunities to tailor the opto-electronic properties at the device level and have achieved impressive results in photo-FETs.

The growing understanding and the rapid advancements in 2D material synthesis, device fabrication, and interface engineering are all promising signs towards the successful incorporation of 2D semiconductors in photo-FETs. As the field progresses, we can anticipate that the unique photo-

responsive features provided by these 2D semiconductors can revolutionize the design and operation of photo-FETs, thereby driving the next wave of optoelectronic devices and systems.

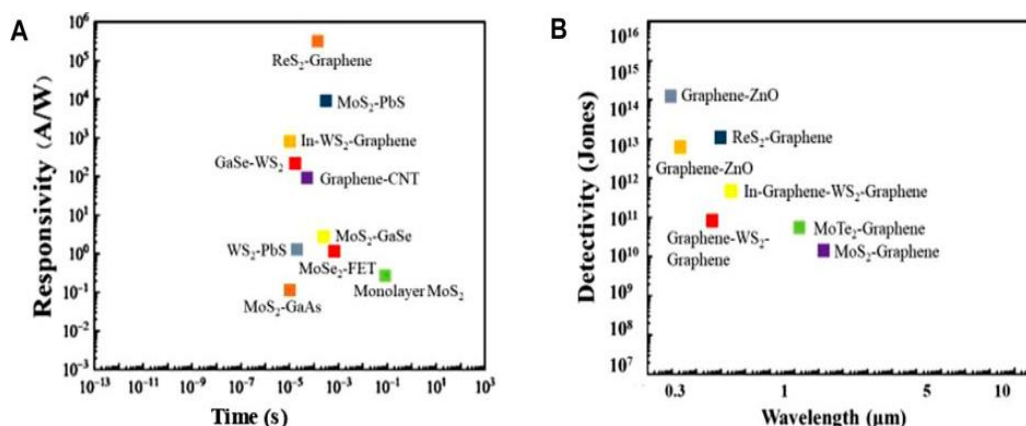


Fig 3. Compare the performance of various two-dimensional material photodetectors [4]. (A) Optical responsiveness of conventional materials and their heterostructures for infrared detection, and (B) optical responsiveness of two-dimensional materials and their heterostructures for infrared detection.

3.3. New materials for pressure sensors and neuromorphic computing

Two-dimensional semiconductor materials have emerged as promising pressure sensor materials by integrating them with conductive microstructural air gaps. These structures take advantage of the unique properties of 2D materials to achieve high sensitivity and high precision pressure sensing. The pressure sensing performance of the pressure sensor based on the CMAG-2D semiconductor transistor is shown in Figure 4. In addition, pressure sensors based on 2D materials show high responsiveness to small pressure changes, which is superior to traditional sensors. 2D material based transparent thin film transistors (TFTs) provide further evidence of these advantages, showing significant pressure-sensitive properties. With fast response, high stability and low power consumption, these devices are suitable for remote pressure monitoring applications such as static pressure profiles, real-time human pulse wave measurements and acoustic detection. [5].

Another exciting application of 2D semiconductors is in neuromorphic computing, where among them there is great potential for tft based on transition metal disulfide compounds (TMDs)s (TMDs) have great potential. The inherent structural flexibility of these 2D materials enables the fabrication of miniaturized devices, opening up new possibilities for compact wearable sensors and flexible display technologies. Furthermore, the TMD-based TFTs have a wide operating temperature range (~ 77 -400 K), making them robust for various environmental conditions and operational requirements, and thus ideal for complex electronic systems.

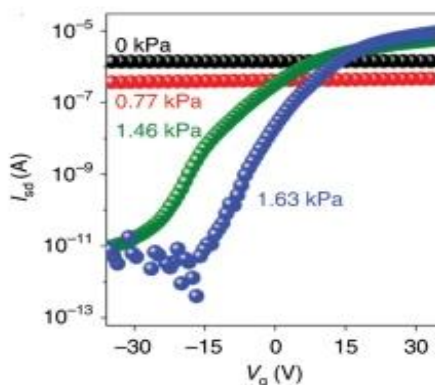


Fig 4. Pressure sensing performance of pressure sensors based on CMAG-2D semiconductor transistors [6]. Transfer curve of CMAG-MoS₂ pressure sensor with $V_{sd} = 1$ V on SiO₂ substrate under different pressures.

4. The challenge of two-dimensional semiconductors in transistors

Venturing into the frontier of integrating two-dimensional (2D) semiconductors into field-effect transistors (FETs) holds great promise but is challenging. These challenges encompass every aspect, from synthesizing the materials to fabricating the devices and addressing performance issues. Overcoming these hurdles is crucial for unlocking the full potential of 2D semiconductors in diverse FET applications.

The synthesis of 2D semiconductors represents the initial hurdle to overcome. Producing large-area, high-quality 2D materials, especially Transition Metal Dichalcogenides (TMDCs), remains a critical challenge. Despite advancements in techniques like chemical vapor deposition (CVD), achieving precise control over layer numbers, domain size, and defect densities remains a significant endeavor [7]. Additionally, the scalability of 2D material production is still in its nascent stage, limiting the feasibility of translating laboratory-scale advancements to industrial-level production.

Due to the unique lattice constant and electronic structure of 2D materials, band alignment problems and the formation of limited barriers between source/drain and semiconductor are caused. This band barrier will cause the contact resistance to increase, affecting the switching characteristics and the device's overall performance. In addition, factors in the manufacturing process, such as suspended bonds, defects, and impurities at the material interface, can introduce additional electron scattering centers in the source/drain contact area, increasing the contact resistance. This requires the optimization of material contact and equipment construction schemes. It is necessary to develop new contact metals, adjust contact methods, or adopt contact engineering techniques to find a solution that strikes a balance between low resistance and high stability to solve the contact resistance problem in two-dimensional semiconductor transistors and further improve their work efficiency in electronic devices.

Any new electronic material, if it is to be widely used in commercial production, its production process must be integrated with existing manufacturing processes. At present, the complementary metal oxide semiconductor (CMOS) process is the main process of large-scale integrated circuit manufacturing. However, due to the unique properties of two-dimensional materials, such as their atomic-level thickness and unique electronic structure, their production process has many unique challenges. This requires the development of new 2D material process technologies compatible with CMOS processes [2]. For example, for steps such as growth, etching and doping of 2D materials, new processes may need to be developed to accommodate the unique properties of 2D materials and ensure that high quality and consistency of materials are maintained during mass production.

Some two-dimensional materials such as black phosphorus (BP), are less stable under environmental conditions, which poses a major challenge for their application in electronic devices. When these materials are exposed to air or moisture, they rapidly oxidize and break down. In this case, the stability and durability of the device during actual use may be seriously affected, thus reducing its practical application value.

5. Conclusion

Two-dimensional semiconductor materials are thin film materials composed of single or multiple layers of atoms, which have attracted wide attention in the field of semiconductor technology. The concept of two-dimensional semiconductor materials was first proposed by Iijima et al in 1991, for which it was awarded the 2010 Nobel Prize in Physics. Since then, many other two-dimensional semiconductor materials have been discovered, including transition metal chalcogenides (TMDs), black phosphorus (BP), silicon, germanium, boron nitride (BN), graphene oxide (GO), tin oxide (SnO₂), etc., which have unique physical and chemical properties. Such as atomic thickness, adjustable band gap, large specific surface area, high carrier mobility, strong light absorption, high thermal conductivity, excellent mechanical strength and flexibility. These properties enable them to achieve superior performance and functionality in a variety of field effect transistor (FETs) types, such as digital, photoelectric, pressure sensitive, brain-like, biological, chemical, thermal, RF, and

quantum FETs. These FETs have a wide range of applications in electronics, optoelectronics, sensing and energy storage devices and are expected to transform the design and operation of the next generation of electronic systems.

For example, Molybdenum disulfide is a typical 2D bandgap semiconductor material, which can be adjusted from a bulk material with an indirect bandgap (1.29 eV) to a single layer material with a direct bandgap (1.9 eV). This allows MoS₂ to have high photoelectric conversion efficiency and sensitivity in photoelectric FETs. Another example is WSe₂, it has relatively high carrier mobility and low contact resistance made of two-dimensional semiconductor materials that enables high switching ratios and low power consumption in digital FETs. In addition, two-dimensional semiconductor materials can also be combined with other materials to form heterogeneous structures, so that more functions and properties can be achieved, such as pressure sensitive FETs and brain-like FETs.

However, the integration of 2D semiconductor materials into FETs also faces significant challenges, such as the synthesis of large area, high-quality 2D materials, optimization of material contact and device structure, compatibility with existing CMOS processes, and stability and durability of 2D materials and devices under environmental conditions. These challenges require further research and development to overcome technical barriers and explore the full potential of two-dimensional semiconductor materials in field effect tubes. Some of the research challenges include the preparation of large area, high quality two-dimensional materials using chemical vapor deposition, mechanical stripping, liquid stripping and other methods. Doping, defects and strain regulate the electronic structure and transport properties of two-dimensional materials. Through the selection and design of metals, semiconductors, insulators and other materials, the contact between low resistance and high control two-dimensional materials and devices is realized. Multifunctional and high performance two-dimensional materials and device structures were constructed by using laminates, heterojunctions and nanostructures. Surface modifications, packaging, environmental controls, and other measures improve the stability and durability of 2D materials and devices.

In conclusion, 2D semiconductor materials are an attractive and promising research topic that can advance semiconductor technology and create new innovation and application opportunities. This paper provides a brief overview of the properties, applications, and challenges of two-dimensional semiconductor materials, as well as their potential in the transistor field, and looks at the current and future directions of this emerging field.

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