Applications of 2D semiconductor materials in electronics and optoelectronics

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Abstract. Due to the demand for the higher performance of electronic and optoelectronic devices, the research of 2D semiconductor materials is very important nowadays. Because of the excellent electronic and optoelectronic properties of 2D semiconductor materials can be applied in many fields. This article mainly introduced the preparation, properties and applications of 2D semiconductor materials. The applications in electronics and optoelectronics are mainly discussed, such logic gates, field effect transistors light emitting diodes and high responsivity photodetectors. Compared to traditional semiconductor materials, 2D semiconductor materials have higher mobility and energy efficiency, leading to higher responding speed and lower energy loss. The flexibility of these materials also makes wearable electronic devices possible. However, they are still short in stability and immature in preparation. Future studies should focus more on the stability and preparation of 2D semiconductor materials and9 make the massive production and application of such high-performance materials plausible.

Keywords: 2D semiconductor; electronic devices; optoelectronic devices.

1. Introduction

2D semiconductor material is a new type of nanoscale material. Compared with traditional semiconductor materials, 2D semiconductor materials have small size, excellent transmission performance and higher energy efficiency. 2D semiconductors have great advantages over conventional semiconductors in improving the performance of semiconductor components. Due to the advantages of 2D semiconductor materials, they have become the research focus of many researchers and have been applied in many fields.

2D semiconductor materials are composed of one single layer of atoms or molecules. Because of this single layer structure, electrons can only move freely in two dimensions at the non-nanometer scale (the movement in the direction vertical to the lattice plane is limited). That leads to quantum confinement. And due to the confinement and the single layer structure, 2D semiconductor materials have higher mobility than 3D materials. Like other semiconductors, a band gap exists in 2D semiconductor materials’ band structure, which means they must be excited or doped to conduct electricity. Also, exciton binding energy dramatically increases because of the confinement, indicating a strong excitonic effect in 2D materials [1]. Moreover, quantum confinement within 2D materials can be used with chemical composition to adjust the optoelectronic properties at nanoscale [2]. In summary, 2D semiconductor materials have great advantages and prospects in many aspects.

In this paper, starting from some excellent properties of two-dimensional semiconductors, several various preparation methods of 2D semiconductors are introduced. Three preparation methods are mainly discussed: an electrochemical approach based on lithium intercalation, a solution-based approach via THAB intercalation and a gas-phase growth approach. The advantages and disadvantages of different methods are compared, and different properties are analyzed. Some important properties of two-dimensional semiconductors are also discussed. For example, the high dispersity of a 2D semiconductor material based on inorganic perovskite nanosheets and the high contrast of a 2D semiconductor device based on Si_3N_4/Si substrates. Owing to the excellent optical and electronic properties of two-dimensional semiconductors, they have widespread applications and promising prospects in electronics and optoelectronics. Some applications of 2D semiconductors in electronic and optoelectronic fields are also presented. The applications in electronics include logic gates and field effect transistors, while the applications in optoelectronics include light emitting diodes and photodetectors. At present, 2D semiconductors already have some applications, and as researchers learn more about the properties of semiconductors, there will be more applications in the future, such as wearable electronic devices. Two-dimensional semiconductor devices are bound to have a broader prospect in the future.

2. 2D Semiconductor Materials

2.1. Preparation and properties

2.1.1. Preparation

In the field of semiconductor, how to prepare the materials is significant and fundamental. Only if high quality 2D semiconductor materials are obtainable can devices based on these materials manufactured. In 2011, Zeng Z et al. offered a plausible way to fabricate monolayer semiconductor nanosheets via an electrochemical process [3]. The intercalation can be controlled by intercalating lithium into layered bulk materials (MoS_2 e.g.) and incorporating these materials as cathode in electrochemical cells. High yield (up to 92%) nanosheets can be prepared after ultrasonication and exfoliation of these compounds in solvents. However, the lithium intercalation led to a phase transition, which resulted in the decomposition of MoS_2 and could affect the product's performance. The phase transition happened because the massive injection of lithium involved an injection of electrons [4]. To overcome the phase transition, Lin Z et al. investigated into the use of THAB molecules as the substitute of lithium [5]. Inserting THAB into MoS_2 layers reduced the injection as THAB molecules are larger than lithium atoms, and thus the phase transition can be prevented. In this study, exfoliation of the layered materials was done by solution-based techniques. Phase-pure 2D semiconductor materials are obtainable via this approach. Moreover, the high mobility of this material indicates its excellent electronic property. The researchers also found out that solution processing and the contact of the nanosheets didn't affect the mobility of the film remarkably, which means the fabrication of large-area and flexible 2D semiconductor is achievable. The phase-pure and high mobility properties are also advantageous for this material. Besides electrochemical and solution-based approaches, gas-phase growth is another powerful way to prepare 2D semiconductor materials. Tan C et al. studied the growth of two-dimensional Bi_2O_2Se on perovskite oxides via chemical vapor deposition [6]. The researchers observed the morphological evolution of the 2D semiconductors and found out that the film grew uniaxially in the initial growth stage and then merged into a continuous and uniform film. Uniform monolayer Bi_2O_2Se can be obtained in optimized conditions. The thickness of Bi_2O_2Se grown on $SrTiO_3$ substrate was congruent with the lattice parameter, indicating that the growth of Bi_2O_2Se was without buffer layers. This wafer-scale epitaxy exhibited high uniformity over the plane and had high mobility, which is a significant electronic property for semiconductors.

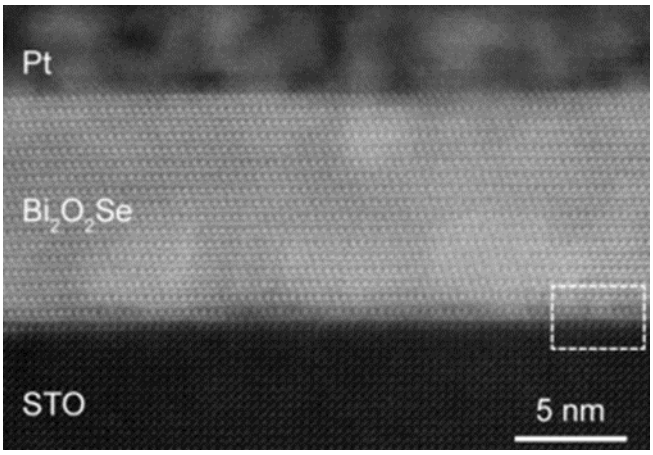

Fig 1. Image of the interface between Bi_2O_2Se film and $SrTiO_3$ substrate [6].

2.1.2. Properties

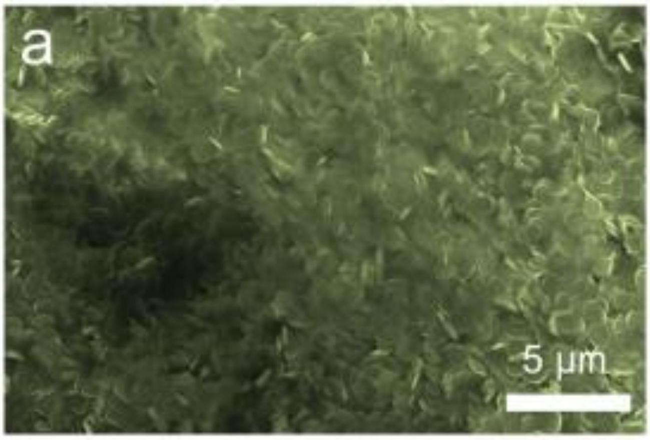

Fig 2. 2D $CsPbBr_3$ nanosheets [7].

Properties of the materials are another major concern in the field of 2D semiconductors. Song et al. studied into a 2D semiconductor material based on inorganic perovskite nanosheets ($CsPbBr_3$) [7]. The synthesis of 2D $CsPbBr_3$ is shown in **Fig. 2**. The synthesis has high yield and purity, with a thickness of approximately 3.3nm. The length of the edge is approximately 1um.

This material has several excellent properties. It has high dispersity compared to other materials. That means it can be dispersed in several types of organic solutions and assembled into films through solution-based processes. Because it can be assembled easily, it can be used to fabricate low-cost and flexible optoelectronic devices. Also, its high light absorptivity makes it suitable for photodetectors. **Fig. 3a** shows that the 2D $CsPbBr_3$ nanosheets have high light absorptivity. The nanosheets have a direct band gap of 2.32eV and an absorbance peak at the wavelength of 515nm, which means it can be an active photodetector for green light. **Fig. 3b** shows a flexible photodetector device. This material has high dispersity, so the nanosheets can be formed on different substrates using various solution-based techniques. This device is flexible due to the 2D geometry of the $CsPbBr_3$ nanosheets and has excellent performance. With high stability, high light sensitivity and outstanding electron transporting properties, it has great potential in optoelectronic devices.

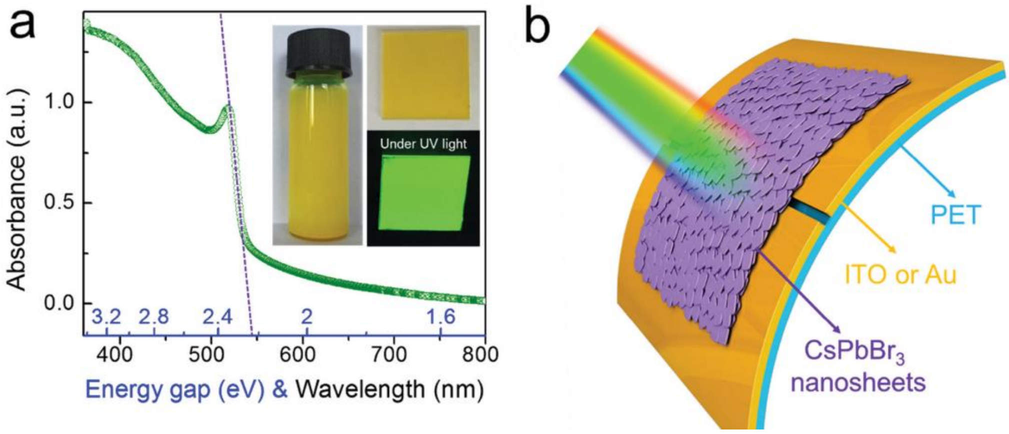

Fig 3. a) Absorption spectrum of the 2D $CsPbBr_3$ nanosheets.
b) A flexible photodetector device based on the 2D $CsPbBr_3$ nanosheet [7].

Rubio-Bollinger G et al. studied the different performance of Si_3N_4/Si and SiO_2/Si functioning as substrates in 2D semiconductor nanodevices [8]. The researchers obtained high-quality flakes of 4 different 2D semiconductor materials attracting much interest: MoS_2, $MoSe_2$, WSe_2 and black phosphorous. Then the flakes are placed onto the two substrates mentioned above: one with a Si_3N_4 layer whose thickness is 75 nm and another with a SiO_2 layer with a thickness of 285nm. The researchers theoretically calculated the thickness to optimize the contrast at the wavelength of 550nm, which is the most suitable for human to observe. By illuminating the samples with monochromatic light of different wavelengths in a range of 450nm to 900nm, the researchers reached the conclusion: using Si_3N_4 as substrates instead of SiO_2 can increase the contrast by 50-100%, regardless of the type of 2D semiconductor. Moreover, using Si_3N_4 as substrates shifts the wavelength who has the largest contrast to about 550nm, which is suitable for human eye observation. This result indicates that it would be easier for human to identify the 2D semiconductors using Si_3N_4 substrates, and this new material has a potential in optical identification and display technology.

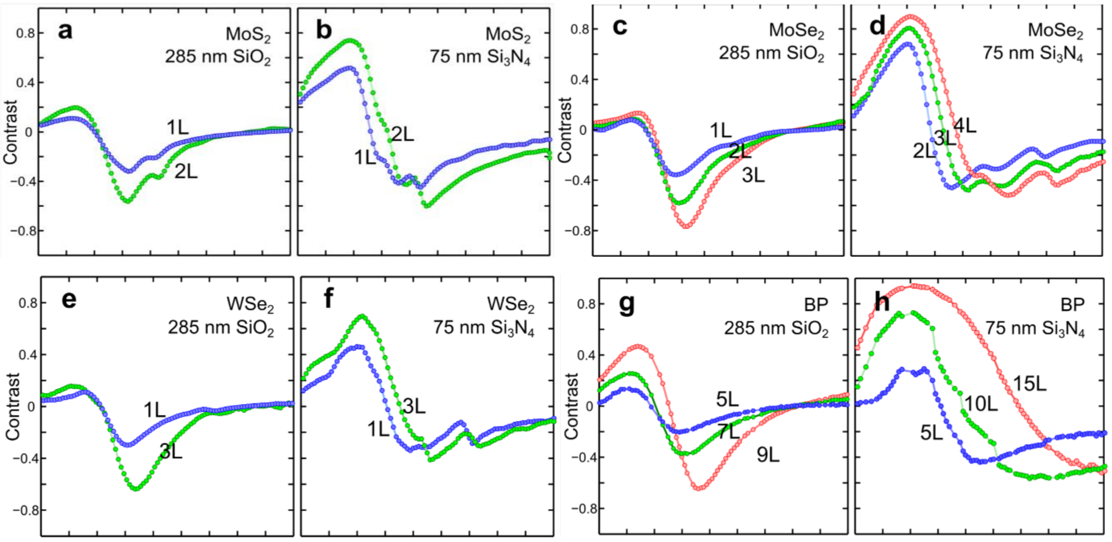

Fig 4. Wavelength dependence of the optical contrast measured for different types of semiconductors [8].

2.2. Applications

2.2.1. Applications in electronics

Because of the excellent electronic and optoelectronic properties of 2D semiconductors, they have widespread applications. The two-dimensional MoS_2 semiconductor based on THAB intercalation mentioned above is plausible to be applied in electronics because of its high carrier mobility and on/off ratio [5]. Due to its phase-pure property, the film can be formed uniformly. The feasibility of large area film makes more complicated devices plausible. The high yield also allows it to be produced massively. This film can be used to fabricate logic gates. MoS_2 thin film transistors were constructed and several basic logic gates were constructed using the local gated transistors as shown in **Fig. 5**. The construction of these basic logic gates is fundamental for the design of integrated circuits. Because complex integrated circuits need thin film transistors of high performance and high yield, this material based on THAB intercalation has large advantage over those based on lithium intercalation, which have relatively lower mobility and yield. Combining the flexibility of the MoS_2 thin film mentioned above, the integrated circuits based on this material can be flexible and extensible. In the future, wearable integrated circuits of different functions can be plausible.

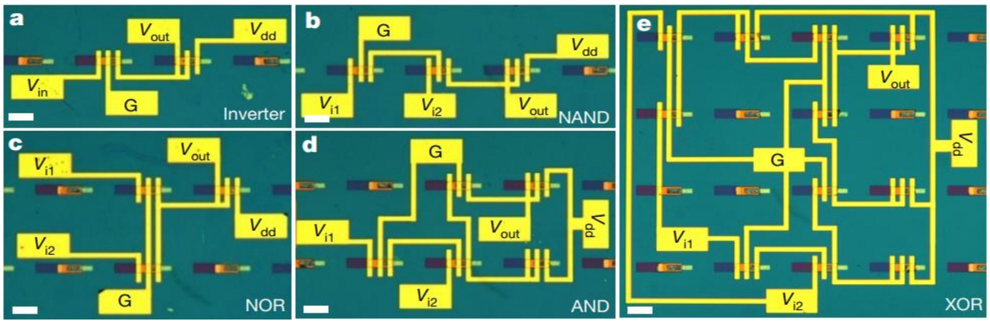

Fig 5. Logic gates based on locally gated MoS_2 thin film transistors. Schematic images of a) inverter, b) NAND, c) NOR, d) AND and e) XOR [5].

Field effect transistors (FETs) are components that are controlled by voltage. FETs have low energy consumption due to its large input resistance, and have high speed and many other excellent properties, so they are preferable in electronic devices. 2D materials have already been in widespread applications. Researchers studied the use of several 2D materials in FETs, such as graphene and transition metal dichalcogenides (TMDs). However, TMD has more applications than graphene due to the fact that TMD has a band gap, which graphene doesn't have. A FET based on monolayer TMD semiconductor channel is shown in **Fig. 6** [9]. The transfer and output characteristics of this transistor are shown in **Fig. 7**. The gate and drain voltage at on-stage is lower than 0.5V, which means the working energy consumption of this transistor is low. Moreover, the subthreshold slope extracted from the transfer characteristics is high, showing that the transistor has high switching speed. The saturation current shown in output characteristics is also important.

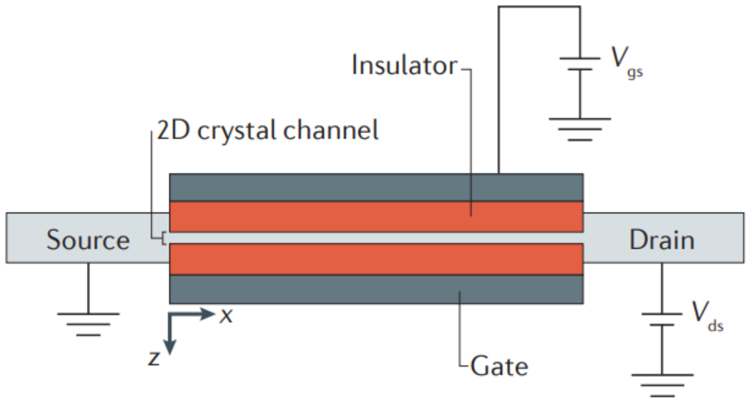

Fig 6. A typical FET based on monolayer TMD semiconductor channel [9].

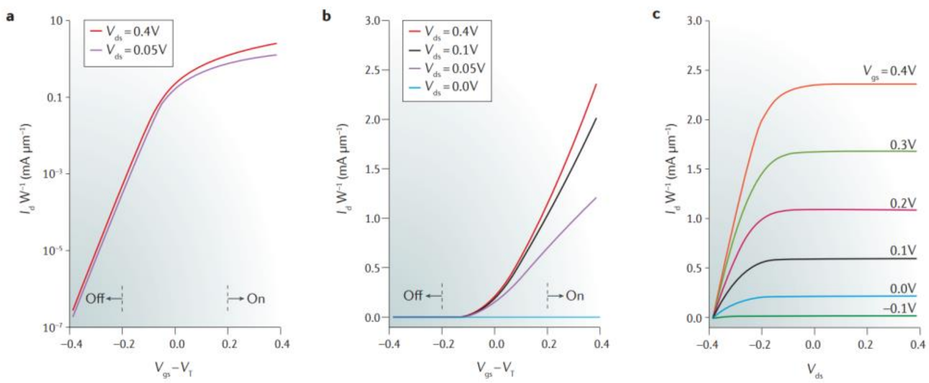

Fig 7. The transfer and output characteristics of the transistor. a) Transfer characteristics in logarithmic form; b) Transfer characteristics in linear form; c) Output characteristics [9].

In addition to high-performance FETs, 2D semiconductor materials enable flexible electronic devices. For 2D TMD semiconductor materials, its band structure can be adjusted by the number of layers, and the band gap width can be adjusted in a large range. Although graphene has high mobility, its lack of energy band makes it difficult to be used in FETs. At the same time, the monolayer TMD material is more flexible and ductile, which can remain undamaged at higher bending degrees. In addition to this, research on TMD is also quite mature and capable of large-scale preparation [10].

2.2.2. Applications in optoelectronics

In addition to applications in electronics, 2D semiconductor materials are also widely used in optoelectronics. Due to the strong excitonic effect of 2D semiconductors, they may achieve effective excitonic emission at room temperature, and this has already been observed in TMDs such as MoS_2 and so on. That means light emitting devices based on 2D semiconductors are feasible. Direct band gap semiconductors are more widely used in light emitting diodes (LEDs) because they do not need a phonon to achieve transition between bands, and this is the same for 2D semiconductors. In light emitting devices, p-n junction is fundamental. In 2014, Pospischil A et al. fabricated a p-n junction based on monolayer WSe_2 [11]. As WSe_2 only exhibits direct band gap in monolayer situations, the researchers ensured it was single layer before fabrication. The electroluminescence intensity was measured under constant current, 50, 100, and 200 nA. The electroluminescence efficiency was also estimated to be about 0.1%. The loss is mainly caused by resistance and non-radiative recombination. The electroluminescence peaks at 1.547 eV, which is 93 meV lower than the photoluminescence peak. This is because an excitonic transition causes the electroluminescence, demonstrated in the experiment. The comparison of electroluminescence and photoluminescence also showed that the spectrum of electroluminescence is more broaden at lower energy. Due to its low fabrication cost and flexibility, this light emitting monolayer p-n junction is expect to have widespread use in different fields.

Another application of 2D semiconductors in optoelectronics is photodetector. Photodetectors are devices that convert optical signals into electrical signals through the photoelectric effect. The major properties of photodetectors are photoresponsivity, photo response speed and the range of spectrum they can respond to. In 2020, Yang Z et al. studied the different performance of photovoltaic and photoconductive 2D semiconductor photodetectors [12]. As a result, photovoltaic 2D semiconductor photodetectors exhibited higher photoresponsivity, while photoconductive 2D semiconductor photodetectors showed higher response speed and stability regardless of reverse bias. The different properties of these two types of photodetectors may lead to different applications in high performance photodetectors.

3. Conclusion

Due to its advantages in electronic and optical properties, two-dimensional semiconductors have become the focus of many researchers. This article introduces the research progress of 2D semiconductor, including the preparation, properties and applications of 2D semiconductor materials. Three methods are described for preparation: electrochemical preparation, solution-based preparation and gas-phase deposition growth. These three preparation methods have their own advantages. Regarding the properties, this article introduces the high dispersity of a 2D semiconductor material based on inorganic perovskite nanosheets. It can be highly dispersed into the solution and assembled into uniform and flexible optoelectronic devices. A 2D nanodevice based on Si_3N_4/Si substrates, which has high optical contrast and can be used in optical identification devices, is also introduced. In terms of the applications, this article mainly discussed some applications in electronics and optoelectronics. The applications in electronics include logic gates and field effect transistors. Its high mobility and high on/off ratio can help fabricate electronic devices with high response speed. The applications in optoelectronics include light emitting diodes and photodetectors. Its high energy efficiency makes energy consumption lower, which is constructive in reducing energy loss. The photodetectors fabricated with 2D semiconductor materials also have high photoresponsivity. In summary, 2D semiconductor materials have many excellent properties compared to traditional semiconductors, such as high mobility and high energy efficiency, which can lead to its applications in electronics and optoelectronics. Moreover, its flexibility makes wearable electronic devices possible. In fact, there are still some shortcomings regarding 2D semiconductor materials. The preparation of these materials is not mature enough, so the fabrication cost is still too high. Also, the stability of this material needs improving. In the future, as the theory of 2D semiconductors is further studied, the shortcomings can be overcome and make the applications more practical.

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