Two-Dimensional Ferroelectric Materials: Synthesis, Characterization and Applications

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Abstract. In recent years, the continuous advancements in microelectronics have driven the evolution of electronic devices towards miniaturization and integration. However, at the nanoscale level, surface and size effects become significant, imposing constraints on the use of conventional bulk ferroelectric materials in contemporary industry. As a result, in the field of materials research, two-dimensional (2D) ferroelectric materials with stable spontaneous polarization and minimal size effects have gained significant attention. These novel 2D ferroelectric materials have great potential for future nano-level ferroelectric applications, enabling high levels of device integration. To begin with, this paper divides 2D ferroelectric materials into two categories: intrinsic ferroelectrics and sliding ferroelectrics. It also discusses the features and current state of research on each of these categories. Next, typical 2D ferroelectric material preparation and characterization techniques are outlined. Additionally, 2D ferroelectric memory devices like ferroelectric diodes (FD), ferroelectric field effect transistors (FeFET), ferroelectric semiconductor field-effect transistors (FeSFET), and ferroelectric tunnel junctions (FTJ) are introduced. Finally, this review also presents expectations and potential challenges in the domain of 2D ferroelectric materials.

Keywords: Ferroelectricity; 2D materials; ferroelectric materials.

1. Introduction

Ferroelectric materials commonly display a reversible inherent polarization that can be modified through the utilization of an externally applied electrical field. These materials' bistable and switchable polarization states have prompted research into a number of applications, including artificial intelligence, logic systems, and non-volatile memories. Ferroelectric materials show promise in addressing issues related to heat dissipation and quantum tunneling in memory devices, making them suitable materials for the development of ultra-high-density memory systems. Consequently, thin films composed of ferroelectric materials are employed to augment data storage density. However, as the thickness of conventional ferroelectric materials decreases, their ferroelectric characteristics undergo a significant decline or may even vanish due to limitations imposed by depolarization field, surface charge accumulation and interface effects.

To effectively address this challenge, researchers are expected to explore two-dimensional (2D) materials that possess ferroelectric properties. The exploration of various 2D materials like transition metal chalcogenides (TMDCs) and graphene, presents unprecedented opportunities for investigating the realm of 2D ferroelectric materials. In comparison to bulk ferroelectric materials, these atomically thin structures lack interfacial suspension bonds, exhibit unique electronic characteristics, and hold potential for integration into innovative electronic and optoelectronic devices. Consequently, they offer promise for applications requiring specific functionality and miniaturization.

Recently, significant progress has been achieved in both theoretical investigations and practical experiments on 2D ferroelectric materials. The theoretical research principles of 2D ferroelectric materials mainly include the first principles method and Landau-Ginzburg-Devonshire theory. Fundamental properties of various 2D ferroelectric materials have been effectively investigated through simulations and calculations using methods like density functional theory (DFT), enabling a comprehensive understanding of their electronic structure and polarization characteristics. However, the limited availability of experimentally obtained 2D ferroelectric materials can be attributed to stringent requirements for structural stability and controllable experimental conditions. Currently,

researchers have discovered ferroelectric characteristics in some 2D materials like WTe_2, $CuInP_2S_6$, In_2Se_3 and so on.

Ferroelectric memory is a highly promising technology for non-volatile memory, providing rapid operation, minimal energy consumption, and exceptional durability. It utilizes ferroelectric materials that possess inherent spontaneous polarization states and are capable of storing binary data in a non-volatile manner. Recently, there has been a growing trend of employing 2D ferroelectric materials in different memory devices like FD, FeFET and FTJ. With further comprehension of 2D ferroelectric materials and device physics, along with advancements in manufacturing technology, future extensive applications are anticipated.

This paper presents a comprehensive overview of the classification, synthesis methods and characterization techniques for 2D ferroelectric materials, as well as recent advancements in memory devices based on these materials. Firstly, the two main categories of 2D ferroelectric materials are introduced. Next, commonly used synthesis methods and characterization techniques, along with their corresponding analysis and examples of application, are discussed. Then, this article provides an in-depth analysis of the utilization of memory devices that rely on 2D ferroelectrics. Finally, potential future developments in this area are also provided.

2. Classification of 2D Ferroelectric Materials

According to the sources of their ferroelectric characteristics, there are two distinct categories of 2D ferroelectric materials: intrinsic ferroelectrics and sliding ferroelectrics. The occurrence of an inherent polarization phenomenon in 2D intrinsic ferroelectrics primarily results from their unique arrangement of crystals, which lacks a center of symmetry. Their unique crystal structure. On the other hand, the asymmetry arising from the relative displacement between atomic layers within the material gives rise to the ferroelectric properties observed in 2D sliding ferroelectrics.

2.1. 2D Intrinsic Ferroelectrics

There are mainly three types of 2D intrinsic ferroelectric materials: 2D ferroelectrics with out-of-plane polarization, with in-plane polarization and without-plane and in-plane polarization.

2.1.1 Out-of-plane polarized ferroelectrics

Out-of-plane polarization reversal in 2D intrinsic ferroelectrics can be accomplished by applying a perpendicular electric field, making them extremely valuable for research purposes. Liu et al. observed the presence of ferroelectric polarization that is oriented out-of-plane in a 4 nm CIPS ($CuInP_2S_6$) wafer at room temperature [1]. The perpendicular orientation reversal of Cu and In ions disrupts the spatial inversion symmetry, resulting in the appearance of spontaneous polarization. In 2023, Hao's research team demonstrated the out-of-plane ferroelectric properties of two-dimensional CCPS ($CuCrP_2S_6$) at room temperature [2]. They attributed these properties to the off-center vertical ordering of copper ions within the layer, leading to spontaneous ferroelectric polarization. The spontaneous polarization value for CCPS at room temperature was measured at 16.05 $\mu C/cm^2$.

However, the modest out-of-plane spontaneous polarization observed in 2D ferroelectrics could limit their use in electronic devices. Therefore, enhancing polarization is crucial for the fundamental research and innovative applications of ferroelectric-based electronic devices.

2.1.2 In-plane polarized ferroelectrics

There is also a growing interest in those demonstrating in-plane polarization. Recently, a study by Naoki et al. presented their findings on the observation of in-plane ferroelectric properties in micron-scale single layer SnS even at ambient temperature [3]. Contrary to conventional knowledge, their research uncovers the presence of robust ferroelectric properties in both odd and even layers of SnS less than 15 layers. This significant discovery opens up possibilities for manipulating the arrangement of multi-layer SnS stacking beyond the constraints imposed by single-layer ferroelectricity. Additionally, Han et al. have provided further confirmation regarding the existence of in-plane

ferroelectric domain structures in 2D Bi_2TeO_5 [4]. They observed typical polarization characterized by displacement and investigated the factors influencing the size and arrangement of ferroelectric domains formed through intercalated ferroelectric domain walls. Consequently, this investigation led to a transition from a state exhibiting ferroelectric behavior to one displaying antiferroelectric characteristics.

2.1.3 In-plane and out-of-plane polarized ferroelectrics

In 2017, Ding et al. were the first to predict ferroelectric properties in In_2Se_3 [5]. They demonstrated that altering the Se atomic layer's position in In_2Se_3 can simultaneously reverse both in-plane and out-of-plane polarization. Alterations in the distance between Se atomic layers and neighboring in atomic layers can explain the observed phenomenon. Subsequent experimental validation confirmed ferroelectricity in both hexagonal (2H) and rhombic (3R) phases of α-In_2Se_3 [6].

2.2. 2D Sliding Ferroelectrics

The occurrence of “sliding ferroelectricity” is observed in non-centrosymmetric vdW structures when there is a displacement of atomic layers, resulting in charge redistribution at the interface and a reversal of inherent polarization. This differs from conventional mechanisms for switching ferroelectricity that depend on the movement of ions.

Sliding ferroelectricity is typically observed in double-layer or multi-layer systems, necessitating the artificial stacking of non-polar 2D materials and significantly expanding the range of available 2D ferroelectrics. Leveraging first-principles calculations, the authors have made a systematic study of the slip ferroelectricity in BX (where X represents Sb, P, and as), YN (where Y represents Al, Ga and in), as well as ZC (where Z represents Sn, Si, and Ge) bilayers with honeycomb-like structures [7]. The results indicate that increasing interlayer distance leads to a decrease in electric polarization while an increase in electronegativity difference between the two components results in an increase in polarization.

Experimental evidence supports the non-polar nature of single-layer WTe_2 due to its lack of central inversion symmetry. However, double and triple-layer configurations exhibit vertical electric dipole moments, leading to spontaneous out-of-plane ferroelectric polarization [8]. Additionally, when two BN sheets are stacked in parallel at room temperature, they display ferroelectric behavior, with charge separation occurring between opposite poles. The introduction of an external electric field causes a reversal of polarization through charge exchange on both sides [9]. Recently, Li et al. demonstrated that intralayer slip can generate ferroelectricity in mirror-symmetric structures using single-layer GaSe, opening up new possibilities for potential applications of this material [10].

3. Synthesis Methods and Characterization Techniques

3.1. Experimental Synthesis

Due to the special structure of 2D ferroelectrics, the techniques used to fabricate them have a significant impact on their practical application. Currently, there are two main approaches to preparing two-dimensional ferroelectric materials: the approach from a higher level to lower levels (top-down) and the approach from lower levels to higher levels (bottom-up).

3.1.1 "Top-down" method

This method mainly includes exfoliation through mechanical means and exfoliation in a liquid medium. Mechanical exfoliation is a widely used technique for extracting 2D ferroelectric materials from their bulk crystals using scotch tape. This method has the potential to generate ultrathin 2D counterparts of all layered bulk ferroelectric materials. By employing mechanical stripping techniques on high-quality 3R phase molybdenum disulfide single crystals, Meng et al. successfully obtained thin sheets of 3R phase molybdenum disulfide with varying layers, which were subsequently utilized for the fabrication of a series of dual-gate FET devices [11]. However, achieving high-quality

sample preparation over large areas can be challenging. Besides, the lattice structure and electric dipole properties of ferroelectric materials can be affected by lattice damage and defects during the mechanical cleaving process, which can subsequently impact their ferroelectric properties.

The liquid phase exfoliation technique is a solvent-based method used to isolate 2D materials from bulk samples. This method is more likely to yield high-quality 2D materials compared to the mechanical exfoliation method, making it highly advantageous. Within this technique, there are two distinct categories: liquid exfoliation through direct means and liquid exfoliation based on intercalation. The first method enables the production of single or few-layered 2D materials through ultrasonic treatment in a solvent, although with slightly reduced efficiency. In contrast, the second method involves the incorporation of various components into 2D materials via chemical or electrochemical means, enabling efficient synthesis of high-yield single-layered nanosheets. In a study conducted by Lin et al. in 2018, they reported on utilizing electrochemical molecular intercalation (specifically Lithium intercalation). They employed quaternary ammonium cations substituted with alkyl chains to effectively accomplish the exfoliation of diverse 2D vdW solids, such as In_2Se_3, which is a typical ferroelectric material.

However, achieving large-scale and cost-effective production of 2D materials through liquid-phase exfoliation remains a significant challenge due to the inherent complexities associated with quality control and size regulation.

3.1.2 "Bottom-up" method

The primary techniques employed in this approach are physical vapor deposition (PVD) and chemical vapor deposition (CVD). PVD utilizes the process of physical evaporation and condensation to produce thin films with unique properties. Recently, low-pressure PVD was utilized by Kong Jing and Vincent Tung's research teams to successfully synthesize high-quality 2D SnSe crystals [13]. Additionally, the growth process was optimized through an investigation of various factors such as pre-annealing of the substrate, duration of growth, temperature variations, and pressure adjustments. Although the PVD process requires the exploration of fewer parameters, the sample size obtained by this technique is small, posing a challenge for subsequent physical research and device fabrication.

To achieve the practical application of 2D ferroelectric materials, it is crucial to produce large quantities and high-quality versions of these materials. The CVD technique usually produces large-scale and high-purity materials, making it an ideal choice for the fabrication of many 2D ferroelectric materials. Weng et al. discovered strong ferroelectric properties at high temperatures in 2D α-In_2Se_3 synthesized by CVD [2]. Currently, in order to achieve materials with specific characteristics, the optimization of the CVD method has attracted much interest. The synthesis of $CuCrS_2$ nanoflakes is achieved by CVD assisted by salt, resulting in the manifestation of switchable ferroelectric polarization even at a reduced thickness of 6 nm [14]. Zhou et al. reported an improved method RFCVD (reverse airflow chemical vapor deposition) is used to achieve the growth of α-In_2Se_3 nanosheets on mica substrates with high quality and uniform atomic-scale properties [15]. The 2D ferroelectrics CTCO ($Cd_7Te_7Cl_8O_{17}$) flakes, with a minimal thickness, are fabricated utilizing the selenium-induced selective-bonding CVD technique [16].

3.2. Experimental Characterizations

The exploration of properties in ultrathin films of 2D ferroelectric materials presents a challenge due to the diminished vertical signals compared to bulk materials. To overcome this, a range of techniques, including scanning tunneling microscopy (STM), piezo force microscopy (PFM), atomic force microscopy (AFM), second harmonic generation (SHG) and transmission electron microscope (TEM) are employed for the detection and analysis of subtle signals, enabling a comprehensive investigation into material characteristics.

3.2.1 SPM

Scanning probe microscopy (SPM), represented by STM, AFM and PFM, has effectively addressed the challenge of visualizing materials at the nanoscale. These techniques offer the

advantages of high resolution, minimal environmental requirements, flexible sample prerequisites, and the absence of heavy metal projection, enabling them to capture the intrinsic characteristics of the samples directly.

STM is an instrument that utilizes the quantum tunneling effect to detect surface structures by converting atomic arrangements into image information. AFM, on the other hand, investigates material properties and surface structures through the detection of weak interatomic interactions between the test sample's surface and a miniature force-sensitive element. Gou et al. employed optimized STM and non-contact AFM (nc-AFM) techniques to perform precise measurements of the atomic arrangement and inter-sublattice charge transfer in Bi, thereby confirming the presence of in-plane electric polarization in a single layer of it [17]. PFM, as another important component of SPM, enables local electrical stimulation of the sample through the probe tip while simultaneously measuring mechanical responses with a sensitivity ranging from 1-100pm/V. PFM serves as a valuable tool for characterizing the electromechanical coupling properties of various materials and finds extensive applications in the performance characterization of 2D ferroelectric materials. Moreover, in addition to vertical detection of piezoelectric signals, PFM can also measure in-plane polarization signals of the sample. In 2024, PFM measurements were utilized to demonstrate the ability to induce field-driven switching between out-of-plane and in-plane ferroelectric properties in 2D $CuCrSe_2$ [18].

3.2.2 TEM

TEM is an electron-beam-based microscopy technique that achieves higher resolution than optical microscopes. Its fundamental principle involves forming images by transmitting electrons through a specimen, taking advantage of the shorter wavelength of electrons to observe nanoscale structures. Yimo Han and colleagues have successfully devised a nanobeam four-dimensional scanning TEM (4D-STEM) technique for mapping 2D SnSe. This method enables the simultaneous identification of stacking properties in the out-of-plane direction and alteration of the lattice structure within the in-plane orientation [19].

3.2.3 SHG

SHG is an optical phenomenon that occurs when the chemical structure lacks central symmetry or antisymmetry, allowing for the observation of even-order nonlinear optical phenomena. The occurrence and extent of SHG depend on the material's second-order nonlinear polarizability. By constructing an SHG microscope, spatial resolution measurements can be performed in either scanning or full-field mode to visualize meso-heterostructures within ferroelectric materials, such as domain structures, non-Issing domain walls, and chiral structures. The outcomes obtained from SHG are commonly employed as evidence for the violation of centrosymmetry, which is a fundamental requirement for the existence of 2D ferroelectricity. Wang et al. employed SHG to analyze the ferroelectric and optical characteristics of $CuCrSe_2$ [20]. The SHG image of the $CuCrSe_2$ crystal exhibits a uniform morphology, indicating homogeneity in its composition. The $CuCrSe_2$ crystal exhibits a Curie temperature of approximately 800 K, which exceeds the values reported for other known 2D ferroelectric materials when considering its SHG intensity and is subject to variations in temperature.

3.2.4 Raman spectroscopy

Optics is a critical tool for investigating the structure and properties of materials. Among the many optical characterization methods for 2D ferroelectric materials, Raman spectroscopy stands out for its advantages, such as high resolution, fast acquisition speed, non-destructiveness to samples, and distinct responses to different materials. Guan et al. used micro-Raman spectroscopy to systematically validate the initial state of antiferroelectricity in GeSe [21]. Besides, a variable temperature Raman study was performed on GeSe to investigate the stable polarization temperature (exceeded 700 K) of it. These results indicate a promising potential for the use of this material in high-temperature applications.

4. 2D Ferroelectric Memory Devices

With the discovery of exceptional characteristics in 2D ferroelectrics (such as inherent polarization state and adjustable non-volatile ferroelectric domains through external fields), memory devices based on them are explored, including FD, FeFET, FeSFET, and FTJ, which exhibit immense potential in the field of non-volatile memory.

4.1. FD

The FD device exploits the utilization of ferroelectric materials to augment current behavior and significantly enhance performance based on its distinctive polarization property, thereby showcasing its exceptional potential in diverse applications. In contrast to conventional unidirectional rectifier diodes, this device exhibits exceptional adaptability as the rectification direction can be altered through polarity reversal of the ferroelectric material, making it distinctly different and offering unprecedented versatility.

In 2018, Wan et al. prepared a switchable room-temperature FD [22]. The FD consists of α-In_2Se_3 thin films encapsulated by graphene electrodes of different thicknesses. Monolayer graphene is used as the bottom electrode, while few-layer graphene serves as the top electrode. This device exhibits noticeable rectification capabilities, with the direction of rectification reversing alongside the out-plane polarization direction of α-In_2Se_3. The on/off ratio of this device is about 10^5, which can be used as a good polarity control.

Given the rapid progress in artificial intelligence, there is an immediate demand for densely packed cross-switch arrays. These arrays are critical for future memory and new computing algorithms. Feng et al. have developed a 2D ferroelectric FFD (fin-shaped diode) [23]. This innovative device integrates a ferroelectric capacitor with a fin-shaped semiconductor channel, sharing the top and bottom electrodes. By using two different ferroelectric materials, this device not only possesses analog and digital storage capabilities but also demonstrates remarkable durability and versatility. It exhibits exceptional performance, such as retention of up to 10^{10} cycles, an on-off ratio of approximately 10^2, a feature size measuring 30 nm, low energy consumption and fast operation. In addition, its simple 2D structure, together with its self-rectifying ratio of 10^4, positions it as a novel electronic building block suitable for the design of passive cross-switch arrays - critical components in future memory computing.

The tremendous potential of vdW FD in future compute-sensor architectures has also been revealed. Fang et al. used a combination of first principles and quantum transport to simulate the electrical and photoelectric transport characteristics of 2D vdW type α-In_2Se_3/NbX_2 (X = S, Se, Te) FD [24]. By adjusting the ferroelectric polarization orientation of α-In_2Se_3, it is possible to modify the local state density of the device, resulting in a change of the rectification direction. This discovery presents novel prospects for the realization of non-volatile storage and bidirectional light response.

4.2. FeFET

FeFET is a semiconductor device that uses the polarization field of a ferroelectric material to control the flow of charge carriers. It replaces the non-polar gate medium (traditional oxide) in the traditional FET. It exploits the material’s ferroelectric polarization property to achieve non-volatile electrical modulation of the channel material. The electric field induced by polarization can be utilized to regulate the conductivity of the channel, thereby enabling non-volatile storage in a ferroelectric manner.

In the early stages of the research, ferroelectric thin films were deposited directly onto the Si substrate to create a metal-ferroelectric-semiconductor (MFS) device structure. This structure replaces the conventional MOSFET's SiO_2 insulation with a layer of ferroelectric material. By reversing the polarization direction of the ferroelectric substance, the modulation of the channel current is controlled. A bottom-gate FeFET device based on GaSe and employing a ferroelectric polarization switch was fabricated [10]. In this configuration, a GaSe nanosheet functions as the

tunneling layer, while a 300 nm thick SiO_2 serves as the dielectric layer. Notably, it was observed that the GaSe-FET memristor demonstrates significant reversibility during ferroelectric resistance switching and exhibits an appreciable LRS/HRS ratio.

However, achieving satisfactory long-term charge retention performance for FeFETs directly fabricated on a Si substrate remains a challenge. Forming the optimal electrical interface between the silicon substrate and polycrystalline ferroelectric film is crucial for improving the ability to retain charges. Therefore, an insulating buffer layer is needed, which can be incorporated between the silicon substrate and ferroelectric film to construct a metal-ferroelectric-insulator-silicon (MFIS) structure. This insulating layer not only prevents interfacial reactions and mutual diffusion but also provides a high barrier to minimize charge injection from the substrate to the ferroelectric film, thereby significantly enhancing device stability and reliability. Si et al. conducted a study where they developed a FeFET by utilizing MoS_2 as the channel material and 2D $CuInP_2S_6$ on top of it [25]. The inclusion of $CuInP_2S_6$ aided in minimizing leakage current while enhancing memory performance by virtue of its high Curie temperature (315 K) and wide bandgap (2.9 eV).

4.3. FeSFET

The FeSFET is an innovative memory device that utilizes a ferroelectric material as the semiconducting layer and an amorphous insulating material as the insulation layer. This innovative design aims to address the issue of reduced retention time resulting from gate current leakage and charge entrapment occurring at the interface between the semiconductor and ferroelectric materials, which has been empirically demonstrated to enhance device performance significantly.

Si et al. reported an application of α-In_2Se_3 as a channel material in a FeSFET device [26]. The fabricated FeSFETs exhibited remarkable performance characteristics, including a wide memory range, an exceptional on/off ratio, a peak on-current of 862 $\mu A\ \mu m^{-1}$, and a reduced supply voltage. It was shown that the FeSFETs exhibit significant promise in surpassing the current capabilities of FeFETs for applications in non-volatile memory.

FeSFETs exhibit exceptional properties that position them as highly favorable candidates for simulating artificial synapses; however, there is a lack of comprehensive investigation into the ferroelectric synaptic weight and the potential for non-volatile multilevel memory in these devices. By exploiting the ferroelectric and semiconductor properties of α-In_2Se_3, Wang et al. have successfully fabricated FeSFETs and demonstrated their promising potential as artificial synapses [27]. The findings provided a promising prospect for the advancement of neuromorphic devices in brain-inspired intelligent systems employing α-In_2Se_3 FeSFETs.

4.4. FTJ

FTJ is a memory device consisting of a metal electrode/ferroelectric material/metal electrode structure. It uses a thin layer of ferroelectric material as a tunneling barrier, which can be altered by manipulating its ferroelectric polarization. These devices demonstrate significant promise for utilization in memory and computing due to their mini power consumption, ability to retain data even without a power supply, and the capability of reading data without causing any damage. However, achieving high levels of tunneling electroresistance (TER) remains an ongoing challenge in these devices.

Most current FTJs have relied primarily on perovskite oxide barriers until the recent usage of 2D vdW ferroelectric materials. The discovery unveils new prospects for the realization of tunnel junctions with cutting-edge functionalities and nanoscale dimensions. Remarkably, the atomic-layer thickness of all 2D FTJs usually exhibits an exceptionally high TER ratio.

In 2020, J. B. Wu and his team achieved a remarkable TER value of 10^7 in an FTJ consisting of graphene/$CuInP_2S_6$/Cr [28]. The regulation of the TER was found to be influenced by the control of the barrier height. In this specific tunnel junction, variations in the ferroelectric polarization field of $CuInP_2S_6$ resulted in a significant shift (approximately 1 eV) in graphene's Fermi energy level, resulting in the notable fluctuations in the conductance across different polarization states. Kang et

al. successfully fabricated FTJs using Au (010) and In_2Se_3 as the top contact, wherein In_2Se_3 represents a 2D ferroelectric substance possessing out-of-plane polarization [29]. They also demonstrated that the metal/ferroelectric material contact not only retains its ferroelectricity but also exhibits an impressive TER ratio of up to 10^4 %. This impressive TER ratio can be attributed to the shift in contact behavior between the metal/ferroelectric material, transitioning from Schottky-type to Ohmic-type during the reversal of ferroelectric polarization. These findings suggests that careful selection of appropriate metal materials enables achieving both substantial TER ratios and enhanced performance in FTJs fabricated using 2D ferroelectric materials and metal contacts.

In research conducted in 2023, Liu et al. investigated the utilization of a combination of a hexagonal IV-VI semiconductor and an α-In_2Se_3 ferroelectric to create 2D vdW heterostructures [30]. The researchers suggested that these heterostructures could be used to produce an in-plane FTJ, which demonstrated an impressive TER with an on/off resistance ratio surpassing 10^4. This finding offers a hopeful strategy for developing ferroelectric memory with high performance by utilizing 2D heterostructures consisting of ferroelectric materials and semiconductors.

5. Conclusions

This paper presents a throughout analysis of 2D ferroelectric materials' classification, commonly used synthesis techniques, characterization methods, and their potential applications in memory devices. The outstanding characteristics exhibited by 2D ferroelectrics make them highly attractive for integration into the rapidly advancing field of memory devices. However, further progress requires the establishment and improvement of theoretical models, the development of efficient fabrication methods, thorough investigations into device durability and stability concerns, as well as comprehensive analyses of interface effects when combined with other materials. It is expected that incorporating 2D ferroelectrics will significantly contribute to enhancing convenience and technological advancements in daily life and industrial production.

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