

REVIEW OPEN ACCESS

Advances in Regulating Strategies and Applications of Ferroelectric Materials

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ABSTRACT

Ferroelectric materials, characterized by their spontaneous and reversible polarization under an electric field, have attracted extensive research interest. Their unique properties render them ideal for applications ranging from data storage and energy harvesting to sensing and catalysis. Driven by the demand for miniaturized and energy-efficient nanoelectronic devices, precise control over ferroelectric performance has become a central focus. This review comprehensively summarizes key strategies for tailoring ferroelectric properties, with a focus on external field manipulation, low-dimensional confinement, interface engineering, and topological structuring. We subsequently highlight recent advances in cutting-edge applications in memory, neuromorphic computing, sensors, energy conversion, and catalysis. Finally, we present future research directions to guide the development of next-generation ferroelectric materials and devices.

1 | Introduction

Ferroelectric materials possess a spontaneous polarization whose direction can be reoriented by an applied electric field [1, 2]. Their unique ferroelectric properties make them of great value in information storage [3–5], sensing detection [6–8], energy collection and conversion [9–11], catalysis, [12–14] and other fields. Ferroelectric materials are critical to advancing micro-nano devices, flexible electronics, and AI hardware [15]. Their properties underpin progress in next-generation technologies such as non-volatile memory, piezoelectric energy harvesting, and electrocatalysis [16–18].

However, the manifestation of ferroelectricity is often hindered by the complex interplay of multiple factors, including crystal structure, size effects, defect states, and interface properties [19–22]. Thus, a fundamental command of ferroelectric switching and

polarization hinges on the ability to regulate these properties, which is the cornerstone of designing materials with tailored performance and novel functionalities [23]. By manipulating key parameters through doping, strain, and interface design, scientists can now tailor ferroelectric materials for a broader range of applications, unlocking emergent phenomena beyond conventional polarization switching [24–27]. Deciphering the fundamental principles of ferroelectric regulation is pivotal for advancing the field. It not only solves key bottlenecks in material performance but also provides the scientific foundation for guiding the creation of new device concepts.

At the application level, ferroelectricity offers distinct advantages. For instance, ferroelectric memory combines non-volatility with high-speed operation, positioning it as a leading candidate for next-generation storage technology [28–30]. By harnessing their unique responsive properties, ferroelectric materials are

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becoming core components for emerging, integrated sensing-energy systems [8, 31, 32]. Leveraging the ferroelectric catalysis and tunneling effects is driving innovations in next-generation technologies, from advanced energy harvesting systems to novel quantum information processing devices [33–35]. Advances in understanding multiferroic coupling and low-dimensional ferroelectric systems are positioning ferroelectric photovoltaic materials to unlock new possibilities in flexible electronics, wearable technology, and neuromorphic computing [36–40]. In summary, ferroelectricity regulation is more than a frontier research topic—it is the key to driving technological innovation by enabling high-performance and multifunctional material systems.

This review systematically expounds on the characteristics of ferroelectric materials and the main strategies for manipulating their properties, focusing on external field manipulation, low-dimensional confinement, interface engineering, and topological structural design. It then summarizes the latest progress in ferroelectric applications in cutting-edge fields such as memory, brain-inspired computing, sensors, energy conversion, and catalysis (Figure 1). Finally, it proposes potential future research directions to provide insights for the development of next-generation ferroelectric materials and devices.

2 | Fundamental Properties and Historical Development of Ferroelectric Materials

2.1 | Fundamental Properties of Ferroelectric Materials

The unique physical properties of ferroelectric materials underpin their diverse applications, from non-volatile memories and microelectromechanical systems to energy harvesters and neuromorphic computing devices [41]. A fundamental understanding of their intrinsic physical properties is therefore essential to unravel the origin of their functionalities and the principles guiding their development. This section explores the key characteristics and historical progression of ferroelectric materials.

2.1.1 | Ferroelectric Domains and Ferroelectric Domain Walls

A defining characteristic of ferroelectric materials is their division into ferroelectric domains—regions where the spontaneous polarization is aligned. The interfaces between these domains, known as domain walls, are not mere boundaries but often possess distinct functional properties [42–45]. The presence of multiple ferroelectric domains is a common manifestation of the material reaching its minimum free energy, a state governed by the balance of competing internal energy contributions. According to the angle n between the polarization directions of two adjacent ferroelectric domains, they can be called n° domains, and corresponding n° domain walls will appear, as shown in Figure 2. The direction of spontaneous polarization is considered to be from negative charge to positive charge. The region with negative polarization charge is defined as the “tail,” and the corresponding region with positive polarization charge is defined as the “head.” If two adjacent ferroelectric domains have the same charge (head to head or tail to tail), boundary charges will

be generated at the domain wall, forming a conductive domain wall (Figure 2b,c). Interestingly, these charged domain walls often exhibit behavior similar to a “Schottky interface” (An interface formed when a metal and a semiconductor are in direct contact, exhibiting special electrical properties.) electrically. Their local band bending and charge transport characteristics can be effectively controlled by the polarization charges at the interface, leading to nonlinear electrical responses such as rectification. Conversely, the charges will compensate for each other, forming a non-conductive domain wall (Figure 2a).

2.1.2 | Polarization Reversal Mechanism

The reversal of polarization direction upon application of an electric field is a fundamental switching operation in ferroelectrics. This dynamic reconfiguration of domains is not only a signature response but also the basis for critical device functions, such as non-volatile memory [46–48]. Mastery of the polarization reversal process is key to both understanding fundamental ferroelectric behavior and tailoring these materials for enhanced performance in memory, sensor, and neuromorphic computing devices [49]. Figure 3a illustrates the kinetic pathway of polarization reversal, which progresses through four primary stages: domain nucleation, forward growth, lateral expansion, and final merging of domains. Initially, nuclei with a favorable polarization orientation undergo rapid longitudinal growth under the applied electric field. The kinetics of polarization reversal exhibit a strong field dependence. At low fields, the process is limited by the rate of domain nucleation. With increasing field, the mechanism shifts to domain wall propagation, where existing domains expand laterally until they coalesce into a single-domain state [50–52].

A hallmark of ferroelectrics is a polarization hysteresis loop under alternating electric fields, as demonstrated by the similar counterclockwise loops in Rochelle salt (Figure 3b) and classical ferroelectric crystals (Figure 3c). These curves reveal a shared switching mechanism despite different material systems [53–55].

The net polarization exhibits a characteristic nonlinear response to the applied voltage. This stems from the collective reorientation of ferroelectric domains, which initially reside in a random configuration at zero bias but become progressively aligned against domain wall pinning effects as the field increases. This nonlinearity arises from the field-driven progression of domain wall motion and the nucleation of new domains. As the voltage increases, a growing fraction of domains progressively overcome the energy barriers and switch their orientation, eventually coalescing into a unified state. The hysteresis loop is defined by two key parameters: the saturation polarization, which occurs when the polarization response levels off, and the remanent polarization, which persists after the electric field is removed. Exceeding the coercive field to achieve saturation must be balanced against the material’s dielectric breakdown strength. When the electric field is reversed, the polarization gradually switches direction through the nucleation and growth of domains with opposite orientation. The field strength required to bring the net polarization to zero is the negative coercive field (V_c^-). Further increasing the reverse field drives the polarization to negative saturation, completing one branch of the characteristic hysteresis loop.

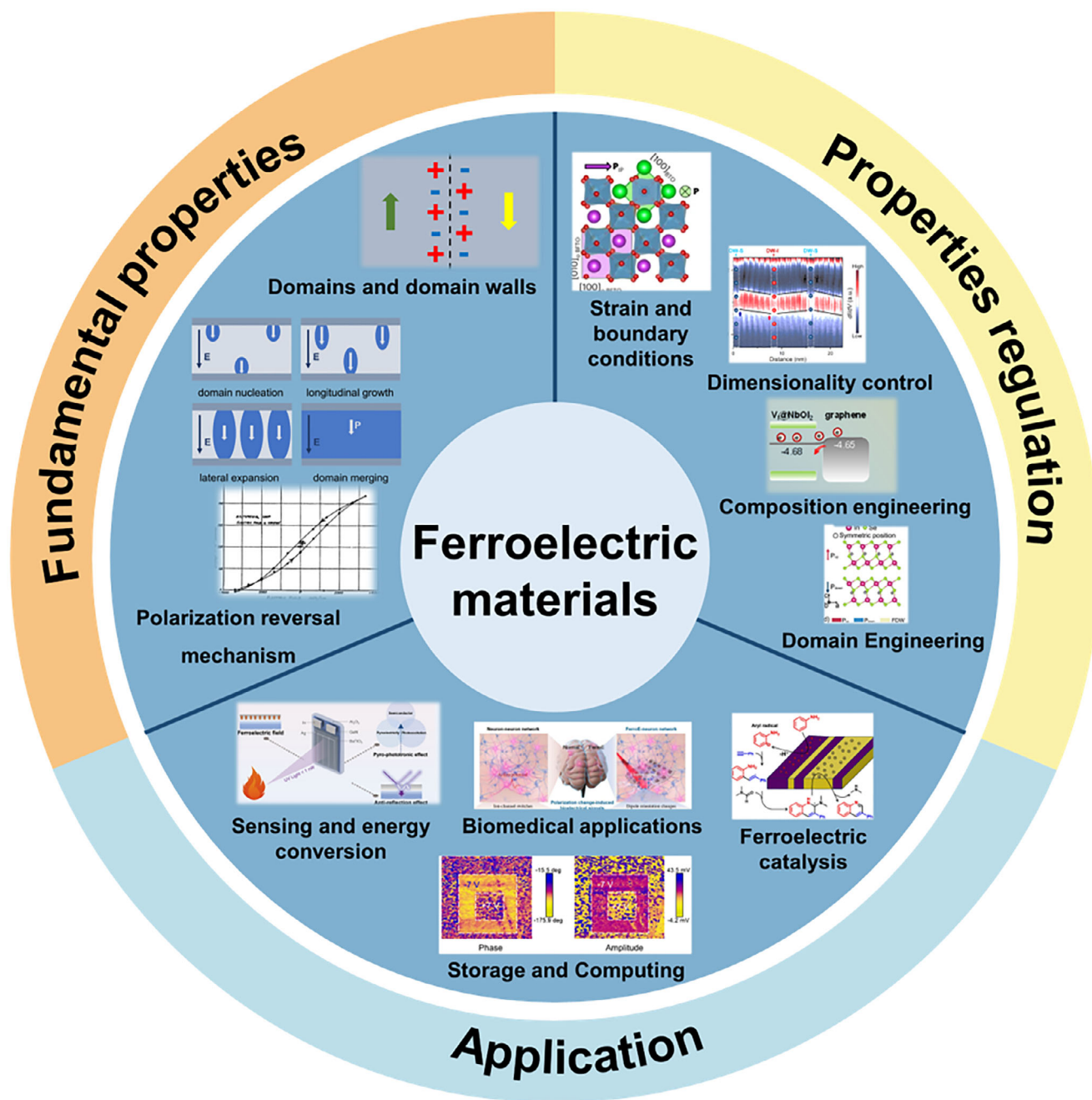


FIGURE 1 | Schematic diagram of the fundamental properties, performance regulating strategies and applications of ferroelectric materials.

2.2 | Historical Development of Ferroelectric Materials

The century-long history of ferroelectrics, beginning with their seminal discovery (Figure 4), is marked by a remarkable expansion of material systems. This progression, from simple salts to complex perovskites [52, 56–58] and modern 2D variants [59–61], underscores the enduring appeal and fundamental potential of controlling spontaneous polarization [62–65].

The study of ferroelectric materials originated from the discovery of the ferroelectricity of barium titanate (BaTiO_3) in the 1940s [66]. This breakthrough not only pioneered the scientific exploration of ferroelectrics, but also promoted their application

in capacitors [67–69], transducers, [32, 70, 71] and piezoelectric devices [72–74]. This was followed by the rise of lead zirconate titanate (PZT), whose exceptional piezoelectric response and strong ferroelectricity propelled it to become the material of choice for decades, enabling advances in transducers, actuators, and energy harvesting devices. During this period, research was largely confined to perovskite-structured ferroelectrics. The paradigm centered on understanding polarization mechanisms, controlling domain structures, and exploiting the macroscopic ferroelectric-piezoelectric effect, thereby establishing the cornerstone of modern ferroelectric science [75–77].

As environmental and health issues become increasingly prominent, traditional lead-containing ferroelectric materials are

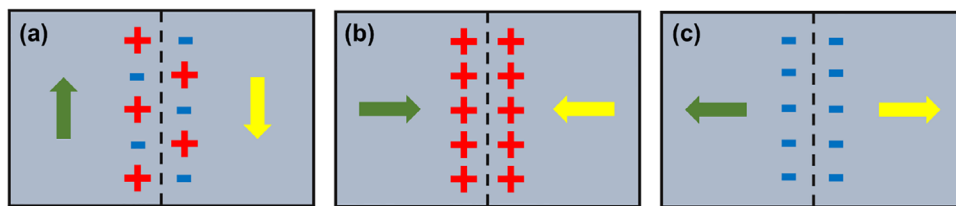


FIGURE 2 | Schematic diagram of (a) non-conductive domain wall, (b) positive domain wall, and (c) negative domain wall in 180° domain wall.

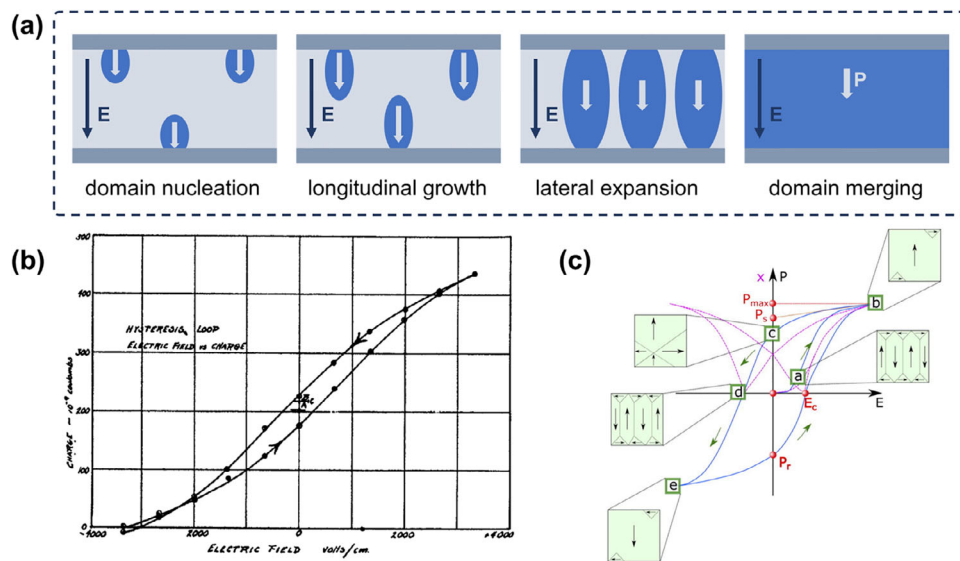


FIGURE 3 | (a) Schematic diagram of the polarization reversal process. (b) Hysteresis curve of the charge in the Roxi salt as a function of the external electric field Reproduced with permission. [53] Copyright 1920, APS Publishing. (c) Hysteresis loop of classical ferroelectric crystals Reproduced with permission. [55] Copyright 2017, AIP Publishing.

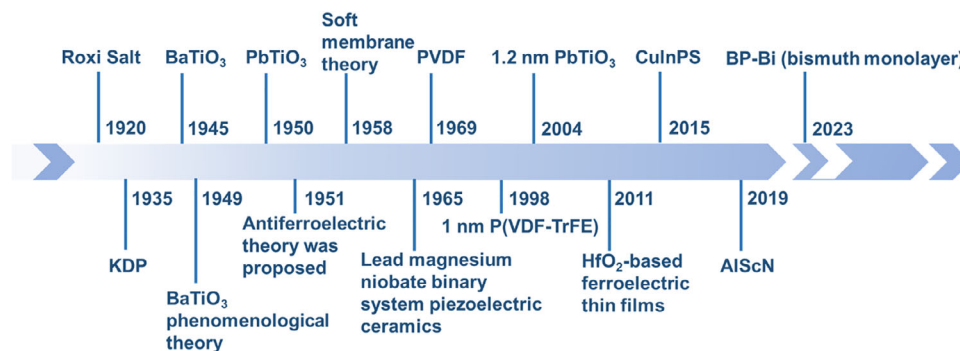


FIGURE 4 | Schematic diagram of the development process of ferroelectric materials.

restricted, prompting researchers to turn their attention to lead-free ferroelectric systems, such as $\text{K}_{0.5}\text{Na}_{0.5}\text{NbO}_3$, $\text{Bi}_{0.5}\text{Na}_{0.5}\text{TiO}_3$, and their solid solutions [78–83]. Through ion doping, external field regulation, and phase structure engineering, researchers have achieved significant improvements in its ferroelectric and piezoelectric properties. At the same time, research on ferroelectric thin films and heterojunctions gradually matured, showing potential applications in non-volatile memory (FeRAM), ferroelectric tunneling junctions (FTJs), and ferroelectric field-effect transistors (FeFETs). During this period, ferroelectric research expanded from traditional bulk materials to low-dimensional thin films, composite structures, and multiferroic coupling systems,

greatly enriching the physical connotations and application directions of ferroelectric materials [84].

The field of ferroelectric materials is undergoing a transformative phase, marked by multidimensional exploration and interdisciplinary convergence. A key catalyst is the emergence of HfO_2 -based thin films, whose CMOS compatibility and scalability are propelling innovations in next-generation memory and logic devices. Concurrently, the discovery of 2D ferroelectrics (e.g., In_2Se_3 and CuInP_2S_6), which retain stable polarization at atomic-scale thickness, breaks the conventional scaling limits and opens avenues for ultra-high-density memory and flexible

electronics. Complementing this trend, ferroelectric polymers and composites offer mechanical flexibility, making them ideal for wearable technology, biomedical sensors, and conformal sensing networks. The future trajectory of ferroelectric materials will be defined by efforts to elucidate fundamental switching mechanisms, precisely harness interface and low-dimensional effects, and deploy these materials in innovative applications—from energy-efficient AI hardware and high-density memory to adaptive bio-integrated devices, ultimately enabling a new class of next-generation technologies.

The field of ferroelectric materials has undergone a significant progression, evolving from classical perovskite systems to lead-free alternatives and, more recently, to the exploration of nanoscale and low-dimensional variants. This evolution reflects a broader trend toward material diversity, sophisticated applications, and a deeper understanding of underlying physical mechanisms.

3 | Regulating Strategies for Ferroelectricity

The commercial application of ferroelectric materials has always revolved around the precise control of the properties of their core spontaneous polarization. Whether it is to reduce the operating power consumption of ferroelectric memory, improve its data retention capability, or maximize the output efficiency of piezoelectric energy harvesters, researchers must face the scientific challenges of how to optimize the polarization intensity, directionally flip the polarization vector, and ensure its long-term stability. To this end, two complementary control paradigms have been developed: one is to use external fields such as electric field, stress, and temperature for dynamic and reversible intervention; the other is to customize its performance from the source through internal engineering means such as chemical doping, interface engineering, and domain structure design during the material preparation stage. Together, these strategies form the cornerstone of modern ferroelectric material research, with the ultimate goal of controlling key parameters such as the amplitude, direction, and stability of spontaneous polarization through external fields or internal engineering. Researchers can precisely design ferroelectric materials to improve the performance of memory, sensors, and energy harvesting devices.

3.1 | Atomic-Level Composition Engineering

A cornerstone strategy in modern ferroelectric research is atomic-level composition engineering. This approach precisely tunes chemical composition via doping, substitution, or stoichiometry control to modulate local lattice symmetry, internal stress fields, and defect distributions. The resulting atomic-scale design stabilizes desired ferroelectric phases, optimizes polarization switching, and mitigates performance degradation such as fatigue. Moving beyond conventional doping, atomic-scale precision in designing thin films, superlattices, and 2D heterostructures has emerged as a paradigm shift in ferroelectric materials research. This strategy has yielded breakthroughs in diverse systems—including HfO₂-based capacitors, perovskite oxides, and van der Waals ferroelectrics—by enabling deterministic control over polarization states and unlocking new physical insights [85, 86].

In HfO₂-based ferroelectric films, the introduction of “chemical pressure” through atomic-level doping can effectively stabilize the orthorhombic ferroelectric phase. For example, differences in the ionic radius of dopant ions such as La³⁺, Y³⁺, or Zr⁴⁺ can induce local lattice distortion, promote the stabilization of noncentrosymmetric phases, enhance remanent polarization, and significantly improve switching durability. Using an optimized atomic layer deposition process, Ansari et al. proposed and demonstrated a novel CMOS-compatible ferroelectric thin-film insulator made from vanadium-doped hafnium oxide (V:HfO₂), as shown in Figure 5a [87]. Comparative electrical performance analysis of metal-ferroelectric-metal capacitors with varying V doping concentrations, coupled with advanced materials characterization, confirmed the ferroelectric behavior and reliability of V:HfO₂. With a high remnant polarization of 20 μC/cm², a coercive field of 1.5 MV/cm², excellent durability (>1011 cycles without failure, extrapolated to 1012 cycles), an estimated 10-year nonvolatile retention period (>100 days measured), and a large grain size of approximately 180 nm, V:HfO₂ is a promising and robust candidate for nonvolatile memory and neuromorphic applications. Through multicomponent solid solution or heterogeneous substitution, random fields and localized disorder effects can be introduced at the atomic scale. Such approaches can lower the domain wall pinning barrier and improve switch ability, while also suppressing thermally driven depolarization processes, thereby increasing the Curie temperature and environmental stability. Jia et al. used the layered heterostructure Hf_{0.5}Zr_{0.5}O₂-ZrO₂ superlattice design to conduct an in-depth analysis and explanation of the correlation mechanism between the charge injection phenomenon in the microscopic polarization reversal process and macroscopic fatigue failure [88]. Based on this, a high-durability (>1012 electric field cycles) ferroelectric thin film material was successfully prepared, which also has a low coercive field (2Ec ≈ 1.7 MV/cm) and a fast polarization reversal speed (Figure 5b). This achievement lays a theoretical foundation for addressing fatigue failure in HfO₂-based ferroelectric memory and provides new solutions for related research. Atomic-level composition engineering, through doping, alloying, and defect manipulation, has demonstrated remarkable success in stabilizing the ferroelectric phase, optimizing polarization switching dynamics, and suppressing leakage and fatigue. Combined with advanced deposition technology and in situ characterization methods, this method is expected to achieve “atomic precision design” of ferroelectricity in the future, providing a solid foundation for the next generation of high-performance non-volatile memory, energy harvesting devices, and emerging flexible electronics. Wang et al. reported the oxidation mechanism of layered oxyhalides and found that heterointerface engineering can effectively regulate the oxidation behavior, as shown in Figure 5c [89]. Due to the low formation energy of I vacancies and the low adsorption energy for O₂, I vacancies will spontaneously form on the NbOI₂ surface, resulting in self-limiting oxidation. For heterostructures with a Fermi level lower than that of the transition state VI@NbOI₂ (such as WSe₂), the I vacancy-induced charge transfer from NbOI₂ to WSe₂ drives the complete oxidation of NbOI₂. For heterostructures with higher Fermi levels than VI@NbOI₂ (such as graphene), NbOI₂/graphene exhibits weak oxidizing properties. This result links the band structure with the oxidation process regulated by heterojunction interface engineering, which is instructive for developing effective strategies to mitigate the oxidation of TMHOs and their heterostructures

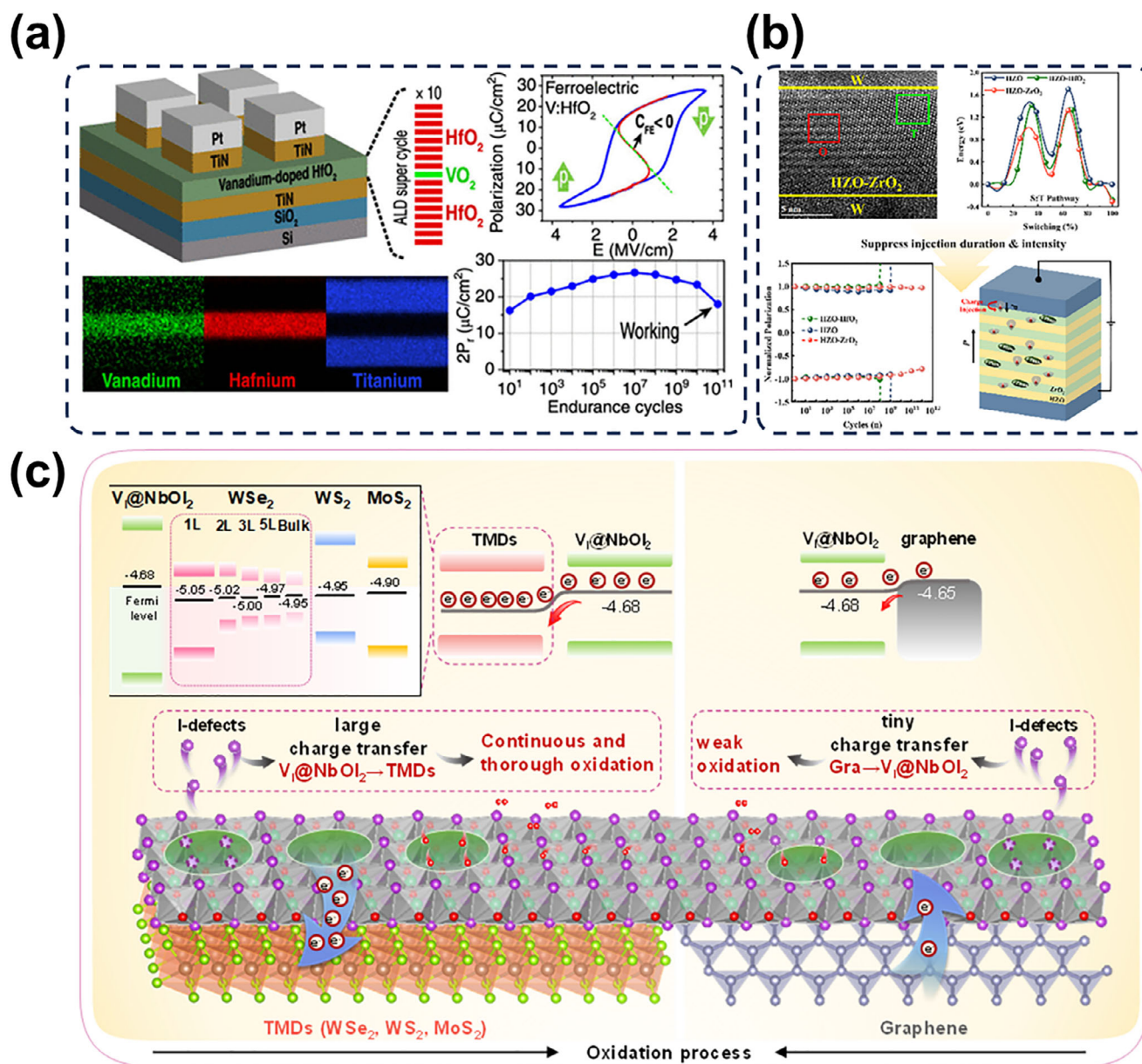


FIGURE 5 | (a) Schematic diagram of an MFM capacitor Reproduced with permission. [87] Copyright 2020, Springer Nature. (b) Schematic diagram of HZO-ZrO₂ ferroelectric superlattice achieving fast switching and low depolarization field Reproduced with permission. [88] Copyright 2025, Wiley-VCH GmbH. (c) Charge transfer-driven oxidation mechanism of VI@NbOI₂/2D materials heterojunction. Insets are energy-band diagrams. The green areas in white circles are the regions after short laser irradiation Reproduced with permission. [89] Copyright 2024, Wiley-VCH GmbH.

for further applications. Atomic-level non-stoichiometric design (such as controlling the concentration and distribution of oxygen vacancies) directly affects carrier capture, leakage channel formation, and polarization stability during ferroelectric switching. By precisely controlling the oxygen partial pressure and composition ratio during atomic layer deposition or molecular beam epitaxy, the defect energy levels can be tuned.

3.2 | Precise Structural Control: From Lattice Strain to Nano-Interface and Dimensional Engineering

Fine lattice control represents a cornerstone strategy for tuning ferroelectric behavior. By tailoring epitaxial strain, interfacial

coupling, and dimensional confinement, this approach enables deterministic regulation of phase stability, polarization orientation, and domain dynamics, thereby linking atomic-scale structural perturbations to macroscopic functional responses [90]. Unlike composition engineering, strain and boundary conditioning rely on external structural constraints and mechanical field modulation to induce lattice distortions. This approach offers distinct advantages in achieving micro-nano structural programmability of ferroelectric materials, enabling dynamic control over domain configurations and polarization states [91]. Strain engineering serves as a powerful tool for stabilizing metastable phases, inducing novel polarization states, and enhancing multifunctional coupling, thereby enabling the creation of designer ferroelectric heterostructures. In perovskite oxides, for instance,

epitaxial strain can stabilize bulk-unstable ferroelectric phases through controlled lattice distortions and octahedral rotations. Remarkably, it can even induce ferroelectricity in inherently non-polar materials like SrTiO_3 and CaTiO_3 , with the polarization strength tunable via strain magnitude and sign. Gradauskaite et al. successfully induced room-temperature stable ferroelectricity by applying uniaxial strain to rare-earth perovskite films and revealed the strain-regulated electro-acoustic coupling mechanism, providing a theoretical and experimental basis for the development of new strain-controllable ferroelectric materials (Figure 6a) [92]. The polarization state of ferroelectric thin films is strongly influenced by the electrical boundary conditions at the interface. The depolarization field is an additional electric field, opposite in direction to the initial polarization, that is generated by polarization charges when a dielectric material is polarized under the influence of an external electric field. This physical effect is particularly significant in the study of ferroelectric materials. By designing the electrode/ferroelectric interface or heterojunction, the depolarization field and charge compensation at the interface can be effectively controlled, thereby stabilizing the polarization in ultrathin ferroelectric layers. In HfO_2 -based ferroelectric systems, interface engineering can even maintain stable polarization switching at a thickness of 2 nm. Wei et al. systematically studied the polarization retention of HfO_2 -based ferroelectric films under different electrode materials and found that the design of polarization continuity at the interface is the key path to breaking the ultra-thin limit (Figure 6b) [93].

At the nanoscale, interfaces and dimensions (layer thickness, superlattice period, and interlayer coupling) become the dominant factors determining ferroelectric properties. By purposefully designing the atomic structure of the interface, constructing functional buffer layers/electrodes, and precisely controlling layer thickness and superlattice arrangement, researchers can modify the local lattice distortion, screening/depolarization fields, domain energy, and domain wall dynamics to achieve the following: (1) Stable polarization in the ultra-thin limit; (2) Induce or switch unconventional polarization states (vortex, closed flow, topological domain); (3) Regulate switching speed, retention, and fatigue characteristics [94]. Sánchez-Santolino et al. discovered a complex polar topology in nanoscale ferroelectric materials (Figure 7a) [95]. The formation of this structure is due to the material's inherent tendency to form uniform polarization and a delicate balance of electrical and mechanical boundary conditions. The ferroelectric-dielectric interface is an important model system where polarization exhibits curled-up behavior, a phenomenon that arises from the action of open-circuit electrical boundary conditions. This condition prevents the accumulation of polarization charge by creating flux-closed domains, leading to the formation of vortex-like structures at the nanoscale. Niu et al. investigated the ferroelectricity and Coulomb screening phenomena that emerge in heterostructures composed of nonpolar van der Waals materials and explored their potential applications in electronic devices [96]. By constructing a variety of van der Waals heterostructures as shown in Figure 7b, the authors revealed the universality of ferroelectricity and Coulomb screening phenomena in a wider range of material systems and studied their origins, mechanisms, and dynamic processes in detail. These findings not only provide a new perspective for understanding the basic physical properties of ferroelectric materials, but also offer new ideas and methods for designing novel multifunctional

electronic devices. Deng et al. experimentally confirmed the existence of ferroelectricity in the 2D magnetic material VCl_3 monolayer and revealed the key role of interface engineering in regulating multiferroicity as shown in Figure 7c [97]. The research results show that by designing van der Waals heterojunctions with specific interfacial interactions, the coexistence of ferroelectricity and magnetism can be achieved in 2D materials. This discovery not only provides new ideas for the study of multiferroic materials, but also lays the foundation for the development of multifunctional devices based on 2D materials. Future research can further explore multiferroics in other 2D materials and achieve more precise control of ferroelectricity and magnetism through interface engineering.

The precise manipulation of the lattice through strain regulation, interface design, and layer thickness boundary effects can not only induce ferroelectricity in non-ferroelectric systems, but also stabilize the polarization state in the ultra-thin limit and stimulate novel topological ferroelectric structures. This type of method emphasizes the synergistic relationship between external constraints and intrinsic polarization, and combined with in situ strain regulation and advanced characterization technology, is becoming the core means to achieve programmable ferroelectricity.

3.3 | Domain Engineering

Ferroelectric domains and domain walls have traditionally been viewed as defects in materials. However, modern research is beginning to recognize them as building blocks with unique functionalities. By controlling the size, shape, and arrangement of ferroelectric domains through various external means (such as electric field, stress, temperature) or internal design (such as using tilted cut substrates), namely domain engineering, it is possible to achieve fine control of the macroscopic properties of materials. Wu et al. investigated the structural and dynamic properties of ferroelectric domain walls in the 2D ferroelectric material $\alpha\text{-In}_2\text{Se}_3$, as shown in Figure 8a [98]. By manipulating the stacking order in the 2D material, its ferroelectric properties can be engineered. They found that 2H and 3R stacked $\alpha\text{-In}_2\text{Se}_3$ exhibit stacking-dependent ferroelectric domain wall properties, which reveal the resistive switching mechanism in ferroelectric semiconductor-metal junction devices. In 3R stacking, the in-plane moving out-of-plane ferroelectric domain walls lead to a larger hysteresis window; while in 2H stacking, the movement of in-plane domain walls and out-of-plane domain walls is more dominant, resulting in a smaller hysteresis window. In addition, under the action of a high electric field, In_2Se_3 will undergo ferroelectric-paraelectric phase transition, in which the 3R stacking realizes phase transition through intralayer atomic slip, while the 2H stacking undergoes a complex process including intralayer bond breaking and interlayer bond reconstruction. Roede et al. revealed through 3D imaging and modeling that domain walls are not planar in 3D bodies, and that curvature and network structure have an important influence on local transport behavior, as shown in Figure 8b [99]. The paper emphasizes the need to consider the 3D morphology and network connectivity of domain walls in practical materials and devices, suggesting that domain engineering cannot be based solely on 2D surface images. This understanding promotes domain network design



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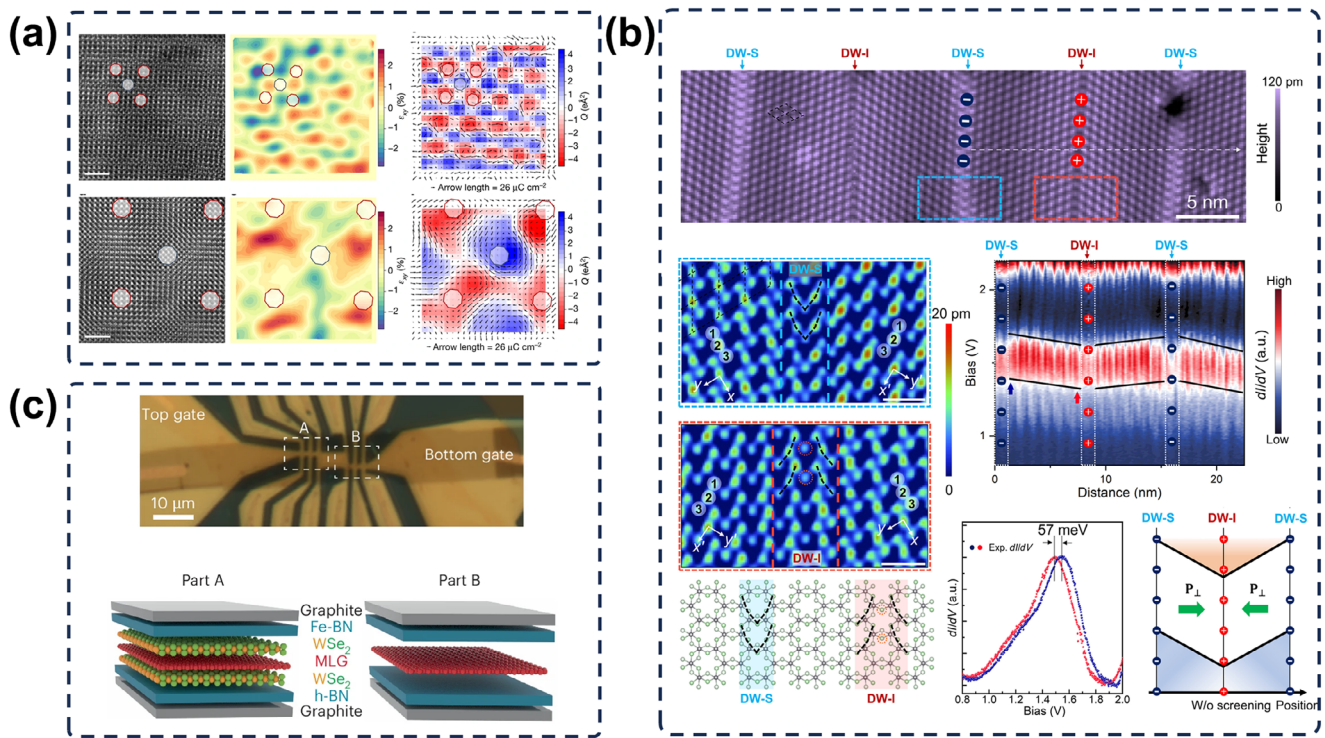


FIGURE 7 | (a) Strain and polarization modulations at twisted BTO bilayers Reproduced with permission. [95] Copyright 2024, Springer Nature. (b) IP electric polarizations are characterized by band bending near DWs Reproduced with permission. [96] Copyright 2025, Springer Nature. (c) Schematic diagram of a single-layer graphene heterostructure device Reproduced with permission. [97] Copyright 2025, AAAS.

and curvature/topology engineering as new control dimensions. Jiang et al. proposed a new method for manipulating ferroelectric domains: reversible and cyclic ferroelectric domain flipping can be achieved only through a unidirectional electric field, breaking the limitation that traditional ferroelectric materials must rely on bidirectional electric fields [100]. The research was completed through collaboration among multiple domestic universities and provides new ideas for new low-power storage and neuromorphic computing devices. The study focused on the van der Waals ferroelectric material CuInP_2S_6 (CIPS) and found that its unique Cu ion migration behavior enables controllable polarization reversal even under a single-direction electric field (Figure 8c). By optimizing experimental conditions (such as using insulating substrates and open-circuit electrical configuration), material damage was effectively avoided, and large-area, reversible, and cyclic domain engineering was achieved.

Domain engineering has undergone a fundamental paradigm shift, from passively accommodating domains to actively designing them as functional elements. This is achieved by exploiting the interplay between electric fields, mechanical stress, chemical potential, and geometric confinement. Such multimodal control at the nanoscale enables the simultaneous customization of both static material coefficients (e.g., Pr , ϵ , d_{33}) and dynamic functional behaviors (such as switching speed, fatigue resistance, and domain wall conductivity).

The breakthroughs achieved in controlling the properties of ferroelectric materials, particularly the precise control of key parameters such as polarization, dielectric constant, and piezoelectricity through domain engineering, interface engineering, and multi-

field coupling, are fundamentally valuable because they provide an unprecedented materials basis for the development of a new generation of multifunctional devices. Essentially, performance tuning stems from the intrinsic physical properties of the material, while practical applications are the result of achieving specific functions. The logical link between the two lies in the fact that, by actively designing and manipulating the microscopic order parameters of materials, we can directionally transform the fundamental response of the material into macroscopic device performance that meets complex needs such as storage, sensing, energy conversion, or neuromorphic computing. Therefore, the following discussion will demonstrate how these precisely controlled ferroelectric materials can serve as core functional units to drive technological innovation in various cutting-edge fields such as information technology, energy, and biomedicine.

4 | Applications of Ferroelectric Materials

The remarkable functional versatility of ferroelectric materials is fundamentally rooted in a set of unique physical properties—most notably spontaneous polarization, the piezoelectric effect, and the pyroelectric effect. These characteristics collectively form the cornerstone that has enabled applications far beyond conventional capacitors and nonvolatile memory. Indeed, the ability to interconvert electrical, mechanical, and thermal energy allows ferroelectrics to permeate a spectrum of cutting-edge technologies, including micro-energy harvesters, high-sensitivity sensors, low-power optoelectronic modulators, and even novel biomedical interfaces. This section systematically dissects the seminal breakthroughs that have propelled this expansion, high-

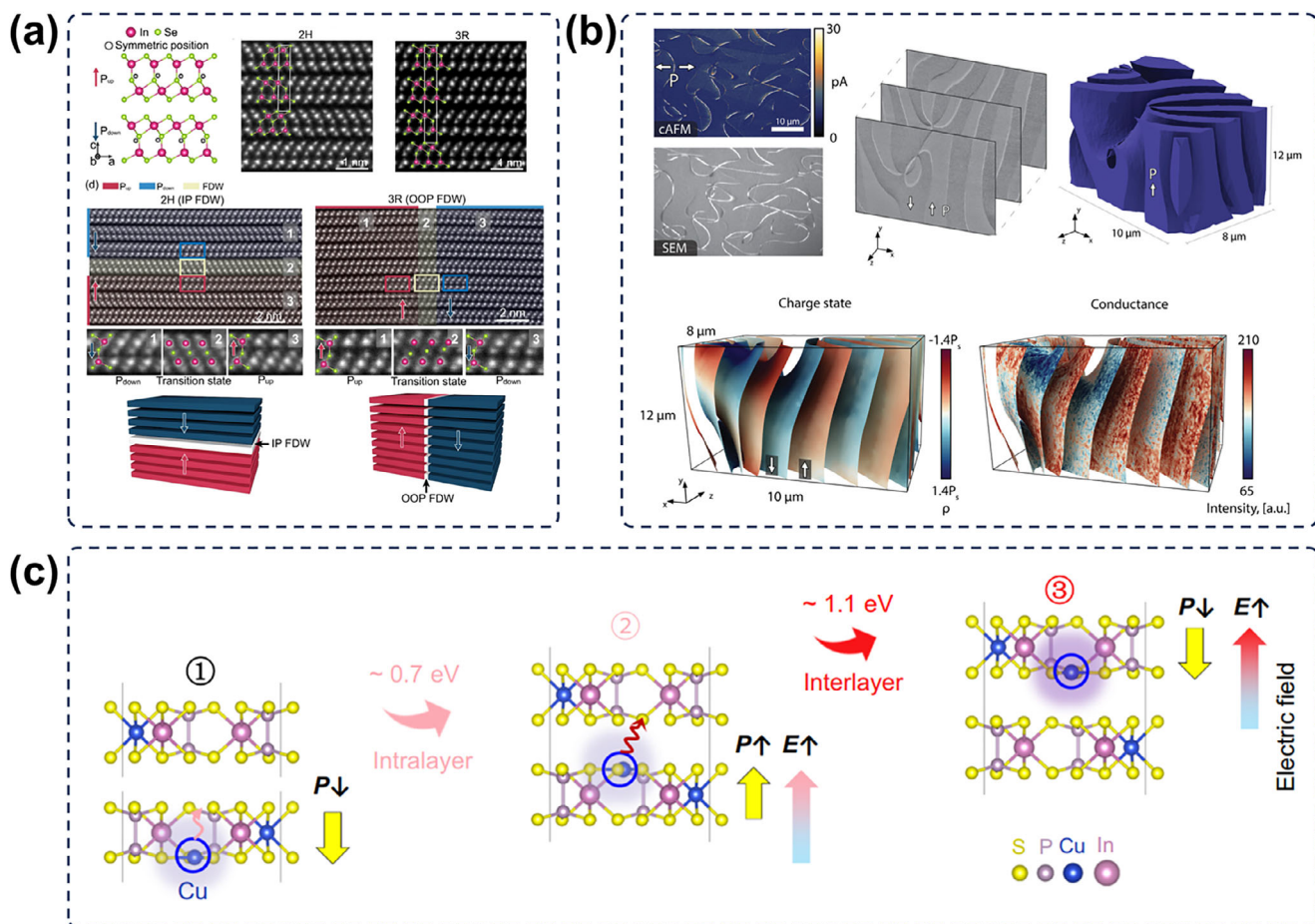


FIGURE 8 | (a) Atomically resolved characterization of the ferroelectric domain configuration in 2H and 3R α -In₂Se₃ Reproduced with permission. [98] Copyright 2024, Springer Nature. (b) Domain wall charge state and electronic transport properties in 3D Reproduced with permission. [99] Copyright 2022, Wiley-VCH GmbH. (c) The schematic of Cu ion migration pathways and polarization switching Reproduced with permission. [100] Copyright 2025, Springer Nature.

lighting how the deliberate manipulation of ferroelectric order parameters unlocks unprecedented functionality across these diverse domains.

4.1 | Storage and Computing

Ferroelectric materials are charting a transformative path in information technology, bridging the gap between high-density, low-power nonvolatile memory and neuromorphic computing hardware. At the heart of this progress are three principal device architectures: the ferroelectric tunnel junction, the ferroelectric field-effect transistor (FeFET), and ferroelectric capacitor-based memristive units. Together, they form the core platform for current research and development. Each architecture leverages distinct aspects of ferroelectric polarization—such as reversible nonvolatility, analog tunability, and ultralow switching energy—to address different tiers of memory and computational requirements, from fast storage to synaptic emulation and in-memory computing.

The ferroelectric tunnel junction sandwiches an ultrathin ferroelectric layer between two electrodes, and changes the barrier height/width by polarization reversal to achieve a large readable

resistance difference (tunnelling electroresistance, TER). Due to its natural multi-level resistance tunability and sub-nanosecond writing capability, it is widely considered to be a strong candidate for synapse-like devices. Luo et al. demonstrated that (111)-oriented PZT-based FTJs can achieve 256 levels of stable controllable states, $>10^9$ times endurance, and extremely low write energy consumption under sub-nanosecond pulses, and further reproduced training accuracy close to the software floating-point baseline on real neural network tasks, demonstrating the feasibility and practicality of FTJs in high-precision, low-energy neuromorphic computing (Figure 9a) [101].

FeFET uses ferroelectric dielectrics as gate dielectrics to achieve non-destructive reading and writing by utilizing remnant polarization to maintain channel threshold displacement, combining the advantages of random access and ease of arraying. Some recent work has further promoted the application of FeFET in industrial-compatible processes and flexible electronic scenarios. For example, as shown in Figure 9b, Li et al. reported a high-performance FeFET based on Zr-doped HfO₂ (HZO) and an ultrathin ITO channel, which not only achieved a large memory window, a high ON/OFF ratio, and a durability of 10^7 – 10^8 times, but also maintained excellent memory and brain-like responses under bending/flexible conditions, demonstrating the unique

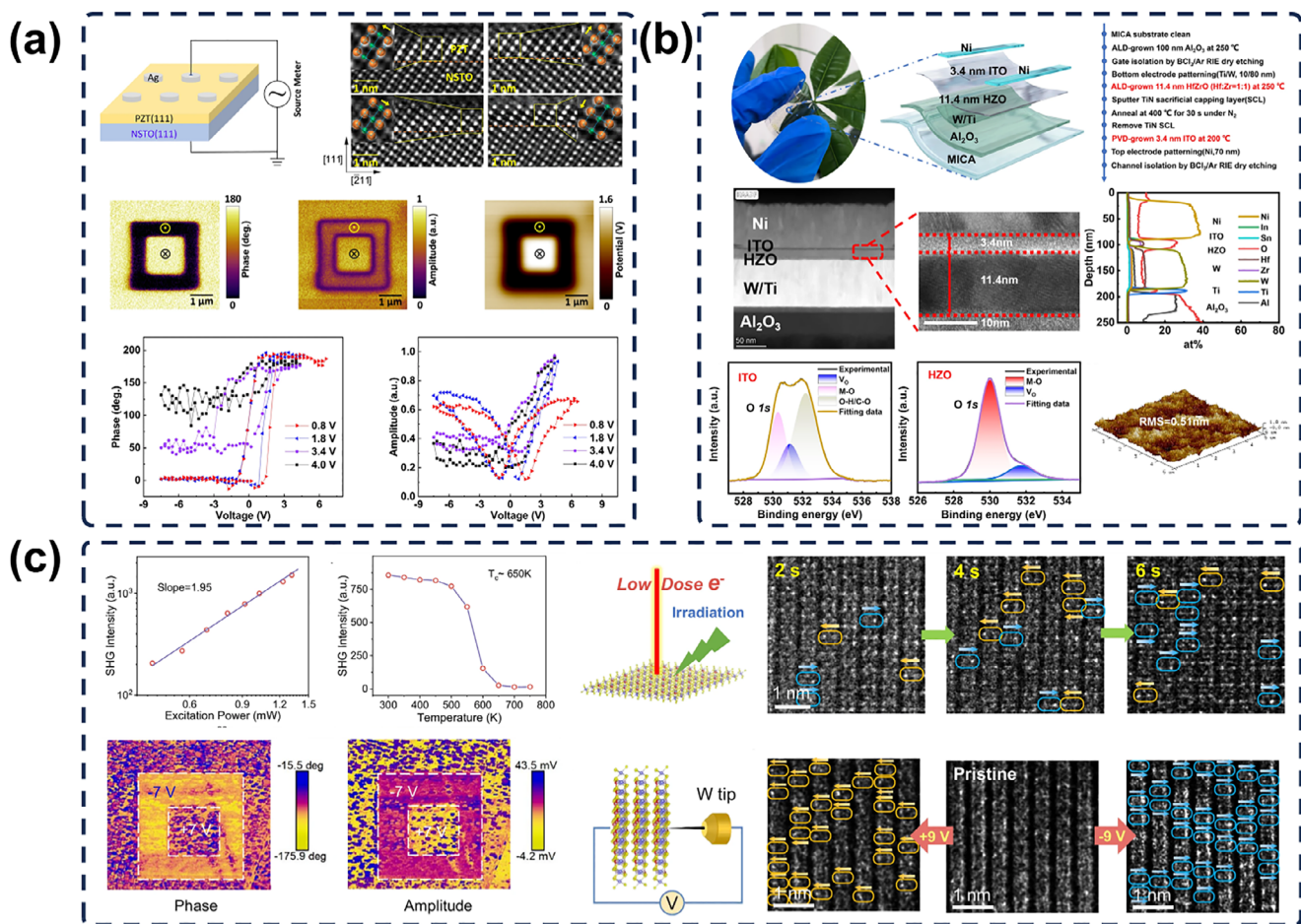


FIGURE 9 | (a) Structural and ferroelectric properties of Ag/PZT/NSTO Reproduced with permission. [101] Copyright 2022, Springer Nature. (b) Schematic and structural characterization of ITO FeFETs Reproduced with permission. [102] Copyright 2024, Springer Nature. (c) SHG, ferroelectric characterizations, and atomic structure of CuVP₂S₆ Reproduced with permission. [103] Copyright 2025, Springer Nature.

advantages of the HfO₂ system in CMOS compatibility and scalability [102].

Since ferroelectric materials have spontaneous polarization characteristics and their polarization state can be controlled by an external electric field, they have broad application prospects in fields such as non-volatile memory, logic devices, and sensors. Since ferroelectric materials have spontaneous polarization characteristics and their polarization state can be controlled by an external electric field, they have broad application prospects in fields such as non-volatile memory, logic devices, and sensors. In contrast, 2D van der Waals (vdW) ferroelectric materials have shown significant advantages in the application of non-volatile memory and next-generation nanodevices due to their dangling bond-free surface, weak interlayer vdW coupling, stable polarization state, and atomic-level integration characteristics. As shown in Figure 9c, Zhao et al. synthesized the 2D material CuVP₂S₆ by spatially confined chemical vapor deposition and verified its ferroelectricity using second harmonic generation (SHG) and piezoresponse force microscopy [103]. Experimental results show that at a thickness of 15 nm, CuVP₂S₆ can still maintain switchable out-of-plane ferroelectric polarization, and its ferroelectric phase transition temperature is as high as 650 K. Using in situ scanning transmission electron microscopy with an applied electric field, the migration behavior of copper ions in

the VS₆ octahedral framework was directly observed, revealing the atomic-level mechanism of its ferroelectricity. In addition, CuVP₂S₆ exhibits excellent optoelectronic synaptic properties and can be used for optical character recognition and neural machine translation, providing new ideas for the development of brain-like computing systems. This research provides a strong experimental basis for the design and application of 2D ferroelectric materials, and demonstrates their great potential in non-volatile memory, logic devices, and brain-like computing.

Ferroelectric materials, with their reversible and non-volatile polarization characteristics, offer diverse technological pathways for building next-generation energy-efficient storage and computing hardware. FTJ, FeFET, and devices based on 2D van der Waals materials exhibit distinct characteristics and complementary advantages in terms of performance, stability, and scalability, due to their different physical mechanisms and material systems. In terms of performance, devices based on PZT, leveraging their tunneling resistance effect, exhibit outstanding performance in terms of analog multi-state control precision and ultra-fast operating speed. They are highly suitable for use as synapse-like units in high-precision neuromorphic computing. FeFETs (such as HZO-based devices), on the other hand, focus more on storage performance, such as achieving large memory windows and high switching ratios. They are suitable as basic units

for non-volatile memory cells or in-memory computing arrays. Emerging 2D ferroelectric materials (such as CuVP_2S_6) exhibit high-temperature stability and unique optoelectronic coupling characteristics, opening new avenues for the development of novel multifunctional devices. In terms of stability and durability, both traditional perovskite materials (such as PZT) and emerging HfO_2 -based materials demonstrate good potential, meeting the basic requirements of mainstream applications. The intrinsic structural stability of these materials allows them to maintain stable ferroelectricity even at ultrathin scales, but their long-term operational stability and uniformity in large-scale manufacturing still require further verification. The most critical difference in scalability lies in compatibility with existing semiconductor processes. HfO_2 -based ferroelectric materials have a decisive advantage due to their high compatibility with standard CMOS processes, especially with back-end process integration, making them the closest route to large-scale industrial applications. Although the FTJ structure is relatively simple, the reproducible and uniform fabrication of its ultra-thin, high-quality ferroelectric layer presents a challenge for large-scale integration. Two-dimensional van der Waals ferroelectric materials represent the future direction of atomic-scale integration and flexible electronics, but the controlled preparation and transfer techniques of large-area, high-quality single-crystal thin films, as well as integration methods with silicon-based processes, remain the main scalability bottlenecks.

4.2 | Sensing and Energy Conversion

Ferroelectric materials demonstrate remarkable potential for advanced sensing and energy conversion systems, a capability fundamentally rooted in their spontaneous polarization and highly responsive behavior under external stimuli—including stress, temperature gradients, and light irradiation. These intrinsic attributes give rise to a range of functional effects, such as piezoelectricity, pyroelectricity, and the ferroelectric photovoltaic effect, which together furnish a robust physical foundation for designing highly sensitive, self-powered multifunctional sensors as well as efficient mechanical-thermal-optical energy harvesters. In recent years, substantial progress in this domain has been achieved through systematic advances across multiple fronts: refined microstructure engineering for enhanced charge separation and domain control, sophisticated external field regulation strategies that dynamically modulate polarization states, and the development of novel material systems—from HfO_2 -based thin films to 2D ferroelectrics—that significantly broaden the operational temperature, stability, and scalability of such devices.

In the field of microstructure engineering and multifunctional coupling, Li et al. have made breakthroughs in their research as shown in Figure 10a [6]. They innovatively used dielectrophoresis technology to precisely program the directional arrangement of samarium-doped lead magnesium niobate titanate ceramic fillers in a polydimethylsiloxane matrix, thereby constructing efficient electrical and thermal transmission pathways within the flexible composite material. Phase-field simulation and experimental results show that compared with traditional randomly distributed composite materials, this directional topological structure improves its piezoelectric response by 114% (sensitivity up to $0.9 \text{ V} \cdot \text{N}^{-1}$) and its pyroelectric response by 131% (sensitivity

up to $38.7 \text{ pA} \cdot \text{K}^{-1}$). The multimodal sensing textile prepared based on this can synchronously and differentially sense pressure and temperature changes, and can be successfully used to monitor human physiological signals. More importantly, they introduced a machine learning algorithm to decouple and analyze concurrent pressure-temperature signals, achieving 100% accurate identification of a variety of materials, providing a new paradigm for the development of intelligent electronic skin and adaptive human-computer interaction systems.

In response to the problems of large surface reflection losses and surface-interface recombination of photogenerated carriers in GaN films in the ultraviolet band, low photon utilization, and difficulty in decoupling devices to achieve high responsiveness and fast recovery performance for ultraviolet light less than 1 nW/cm^2 , Dong et al. proposed reducing surface reflection losses through a ferroelectric anti-reflection layer, reducing dark-state current and surface-interface recombination of photogenerated carriers through a ferroelectric polarization field, and shortening the response recovery time through the thermoluminescent electronic effect of ferroelectric films and GaN [104]. As shown in Figure 10b, the GaN/BaTiO₃ ferroelectric heterojunction prepared by the authors achieved decoupling of high responsivity and fast response recovery to ultra-weak ultraviolet light of 0.68 nW/cm^2 , and was verified by flame detection. The anti-reflection effect is achieved by preparing a 20 nm thick directionally grown BaTiO₃ film on the GaN surface, which significantly reduces the reflection loss of the incident light on the GaN surface. At the same time, the remnant polarization field of the ferroelectric film can regulate the heterojunction barrier height to effectively suppress the dark state current to 5 pA, thereby improving the minimum detection limit of the device. The polarization significantly enhances the thermoluminescent electronic effect of the ferroelectric film, improving the device's responsivity and response speed. The device's responsivity to 0.68 nW/cm^2 UV light is 46.631 mA/W , with a specific detectivity of 3.901×10^{13} Jones and a response recovery time of 18/13 ms.

The applications of ferroelectric materials in the field of energy conversion mainly include mechanical energy harvesting (piezoelectric nanogenerators), thermal energy harvesting (pyroelectric nanogenerators), and light energy conversion (ferroelectric photovoltaic devices). Zhang et al. reported a piezoelectric nanogenerator based on the 2D ferroelectric material (CIPS) CuInP_2S_6 (CIPS) [31]. Through ferroelectric polarization, the device generated a short-circuit current of 760 pA at a tensile strain of 0.85%, which is 3.8 times higher than that of the unpoled sample. Piezoelectric force microscopy and Raman analysis showed that ferroelectric polarization significantly enhanced the effective piezoelectric constant of CIPS nanosheets, promoted the in-plane migration and out-of-plane hopping of copper ions, and was the key mechanism for performance improvement. This PENG can not only collect biomechanical energy, such as human wrist joint movement (Figure 10c-i), but can also be combined with deep learning technology for speech recognition (Figure 10c-ii). The classification accuracy of a series of letter sounds is as high as 96%, demonstrating its broad prospects in wearable electronics and Internet of Things sensing.

Ferroelectric materials exhibit diverse and promising applications in sensing and energy conversion. Their core driving

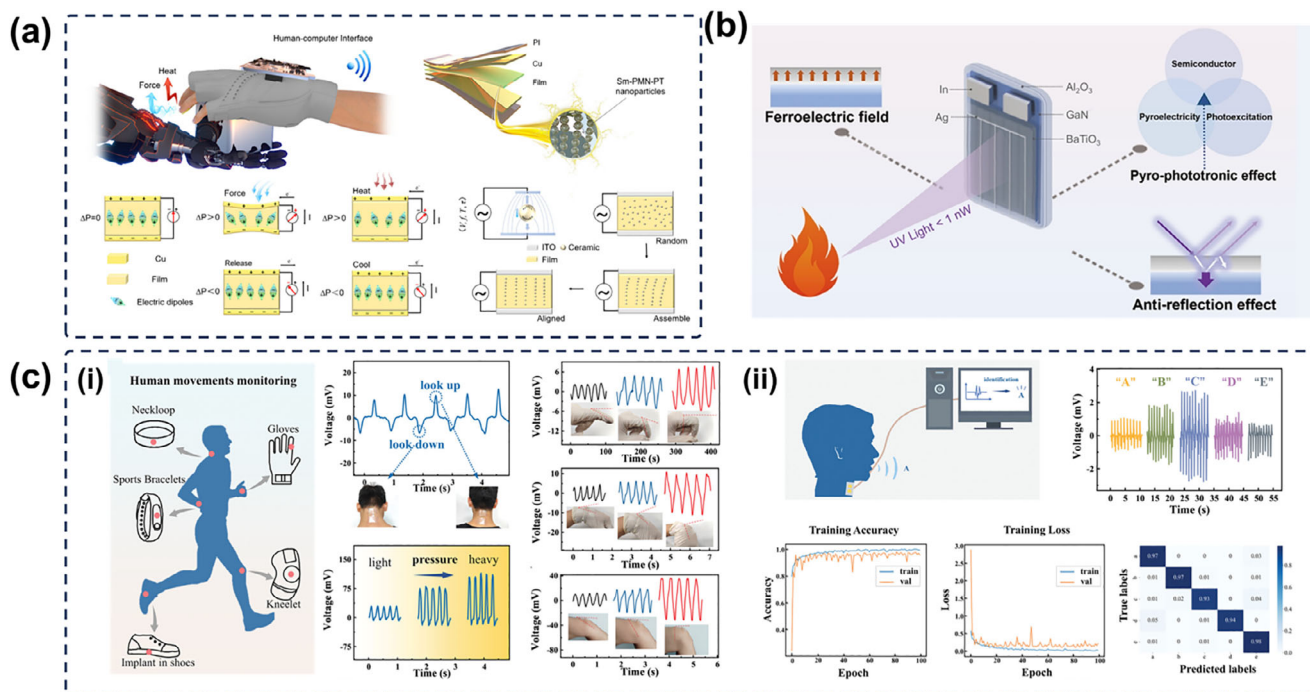


FIGURE 10 | (a) A wearable multimodal sensory system based on the programming ferroelectric nanocomposite Reproduced with permission. [6] Copyright 2025, Wiley-VCH GmbH. (b) A self-powered UV photodetector for flame detection by coupling ferroelectric field, anti-reflection effect, and pyro-phototronic effect Reproduced with permission. [104] Copyright 2024, Elsevier. (c) (i) The application of CIPS-based PENG as wearable devices and (ii) the combination of CIPS-based PENG and deep learning techniques as a sensor for speech recognition Reproduced with permission. [31] Copyright 2023, Wiley-VCH GmbH.

force lies in the highly sensitive response of spontaneous polarization to external stimuli (force, heat, light), giving rise to piezoelectric, pyroelectric, and ferroelectric photovoltaic effects. Current research is advancing device performance toward higher sensitivity, intelligence, and integration through three main approaches: microstructure engineering, external field control, and new material systems. Different material systems and device architectures exhibit differentiated characteristics in terms of performance, stability, and scalability. Ferroelectric sensing and energy conversion technologies are developing along three main lines: “macro-scale flexible composites,” “high-performance heterojunction integration,” and “micro-scale two-dimensional new materials.” These correspond to different application scenarios such as distributed flexible sensing networks, high-performance dedicated detection devices, and ultra-thin multi-functional integrated systems. In the future, the development of this field will rely more on multi-scale material design (from atomic structure to macroscopic composite materials), synergistic control of multiple physical fields (electrical, mechanical, thermal, and optical coupling), and deep integration with traditional semiconductors, flexible electronics, and artificial intelligence algorithms. This will ultimately drive the realization of self-powered, intelligent, and highly environmentally adaptable next-generation sensing and micro-energy systems.

4.3 | Ferroelectric Catalysis

Ferroelectric materials offer a uniquely dynamic and tunable platform for catalytic applications, leveraging their spontaneous polarization and the ability to reversibly switch polarization

states under external stimuli. This functional adaptability has positioned them as promising candidates in several emerging domains, including energy conversion catalysis (e.g., water splitting and CO₂ reduction), environmental remediation (pollutant degradation), and organic synthesis. The catalytic performance of ferroelectric systems originates from three fundamental electromechanical coupling mechanisms: the spontaneous polarization effect, which establishes built-in electric fields that promote charge carrier separation; the piezocatalytic effect, where mechanical stress induces polarization changes and interfacial potentials; and the pyrocatalytic effect, which harnesses temperature variations to generate transient voltages for redox reactions. These effects can operate synergistically, enabling catalytic behavior that is responsive to multiple physical fields.

As shown in Figure 11a, Hu et al. reported an organic-inorganic hybrid perovskite ferroelectric 3,3-difluorocyclobutylammonium copper chloride and used it for the first time in alkane oxidation reaction [105]. This study optimized the synergistic effect of ferroelectric polarization and catalytically active sites through molecular engineering strategies, and achieved a catalytic turnover number of up to 2402 under ultrasonic stimulation, which is 1200 times higher than that of traditional inorganic ferroelectrics (such as lithium niobate). Through Raman spectroscopy and high-resolution X-ray photoelectron spectroscopy, the research team confirmed the role of the Cu²⁺ metal center and the organic ammonium group as dual active centers, while scanning Kelvin probe microscopy directly observed the regulation mechanism of the polarization field on the adsorption energy of the reactants. This work not only demonstrates the high efficiency of molecular ferroelectrics in catalysis, but also lays the foundation for expan-

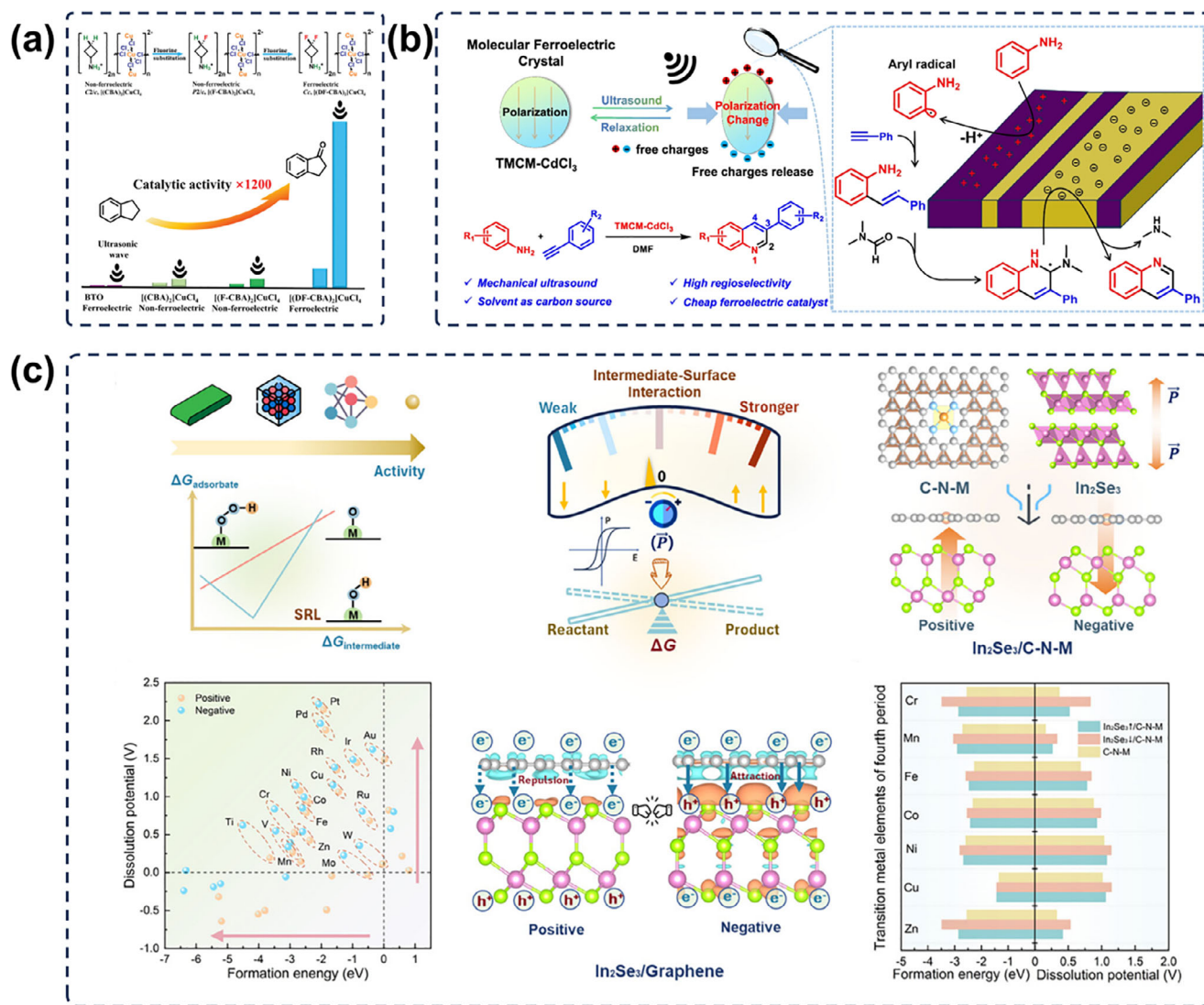


FIGURE 11 | (a) Schematic diagram comparing the activity of inorganic and molecular ferroelectric catalysis Reproduced with permission. [105] Copyright 2024, Wiley-VCH GmbH. (b) Ferroelectric catalytic annulation for 3-arylquinolines by molecular ferroelectric crystal TMCM-CdCl₃ under ultrasonic conditions Reproduced with permission. [33] Copyright 2024, Springer Nature. (c) Catalyst model and stability screening of the ferroelectric In₂Se₃/C-N-M heterostructures Reproduced with permission. [106] Copyright 2025, Wiley-VCH GmbH.

sion to photoelectric coupling reactions and chiral catalysis due to its advantages of solution processing, low acoustic impedance (matching with the solvent to promote energy transfer), and structural tunability.

Liao et al. reported the application of the molecular ferroelectric crystal TMCM-CdCl₃ in the synthesis of quinoline derivatives (Figure 11b) [33]. Using N, N-dimethylformamide as solvent and carbon source, they synthesized a pharmaceutical quinoline compound in a one-pot [3+2+1] cyclization reaction with a yield of 92%. Compared to the inorganic ferroelectric BaTiO₃ and piezoelectric ZnO, TMCM-CdCl₃ exhibits significantly higher catalytic activity and is recyclable. Mechanistic studies indicate that its activity stems from the catalytic effect of ferroelectric domain walls. Under ultrasonic stimulation, the spontaneous polarization direction of the material changes, resulting in localized charge enrichment at the domain walls, which acts as active sites to reduce the C—H bond activation barrier. Furthermore, the multiaxial ferroelectricity (12 equivalent polarization directions)

and high Curie temperature (400 K) of TMCM-CdCl₃ ensure polarization stability during catalysis. This work proposed the concept of “ferroelectric domain wall catalysis” for the first time, breaking through the limitations of activity decay in traditional piezoelectric catalysis and opening up a new path for the application of molecular ferroelectrics in organic synthesis.

The oxygen evolution reaction is a core half-reaction for renewable energy conversion, but its four-electron transfer process has slow kinetics, which seriously restricts the efficiency of water electrolysis. Although single-atom catalysts can maximize metal utilization, traditional substrate materials cannot dynamically regulate the adsorption energy of intermediates, resulting in activity being limited by the linear scaling relationship (SRL). Ma et al. used the spontaneous polarization characteristics of ferroelectric materials to provide a new idea for solving this problem. Its polarization direction can be flipped by an external electric field, dynamically controlling the interface electronic structure, thereby breaking through the SRL limitation [106]. As

shown in Figure 11c, the interface in the negative polarization direction ($P\downarrow$) generates electrostatic attraction due to charge accumulation, and the formation energy (E_f) is 0.2–0.5 eV lower than that in the positive polarization direction ($P\uparrow$). Dissolution potentials (U_{diss}) were generally higher than 1.2 V vs. SHE, with Ir, Ru, and Rh systems performing exceptionally well in both acidic and alkaline environments. Polarization switching enabled the Ir system to achieve a “hybrid mechanism” across a wide pH range, with overpotentials (η) as low as 0.07 V, surpassing the traditional theoretical limit of 0.37 V.

Ferroelectric catalysis is emerging as a transformative paradigm that challenges conventional thermal-driven catalytic processes. By leveraging polarization-switchable surface charges and built-in electric fields, it introduces unprecedented modes of catalytic activation. Moving forward, a deeper mechanistic understanding of charge transfer dynamics at the catalyst-reactant interface, coupled with advanced material design and system integration, will be crucial to fully exploit its potential in sustainable energy conversion, green chemical synthesis, and innovative biomedical applications.

Ferroelectric catalysis, as an emerging interdisciplinary field, centers on utilizing the tunability of ferroelectric polarization to dynamically control the catalytic interface, thereby overcoming the trade-off limitations between activity and selectivity in traditional thermal catalysis. The three material systems discussed in this section—organic-inorganic hybrid perovskite ferroelectrics, molecular ferroelectric crystals, and ferroelectric substrate-supported single-atom catalysts—represent innovations in three different dimensions: molecular engineering, domain engineering, and interfacial electronic engineering. They exhibit distinct differences and complementarities in catalytic performance, mechanistic stability, and system scalability. The field of ferroelectric catalysis is progressing from an initial stage relying on intrinsic material effects to an advanced stage involving the active construction and control of catalytic microenvironments through sophisticated multi-scale design (molecular/domain/interface). The key to future development lies in deeply understanding and coupling the interaction mechanisms between various physical fields (electric, acoustic, optical, and thermal) and catalytic processes, and achieving an optimal balance between structural stability, polarization tunability, and process scalability for specific reaction systems. This will give rise to a series of highly efficient, intelligent, and switchable next-generation catalytic technologies in areas such as green synthesis, energy conversion, and environmental remediation.

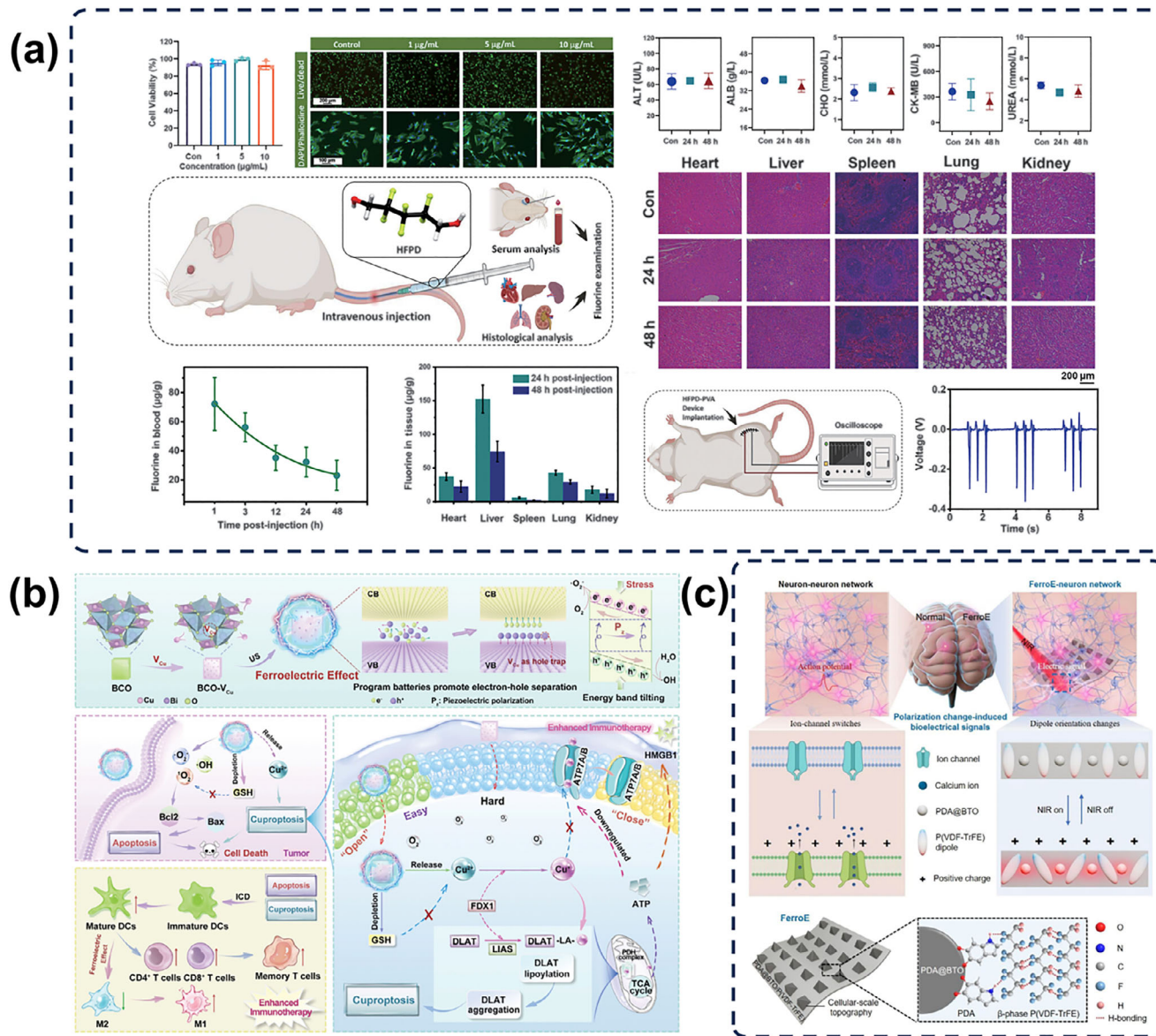
4.4 | Biomedical Applications

Ferroelectric materials, characterized by their stable spontaneous polarization and the capability to reorient this polarization under an external electric field, are emerging as a uniquely versatile platform for biomedical applications [107]. Their intrinsic physical effects—including the piezoelectric effect (converting mechanical stress to electrical signals), the pyroelectric effect (responding to temperature changes with surface charge), and a pronounced nonlinear dielectric response—allow them to act as transducers among mechanical, thermal, and electrical energy domains [108]. This multi-physical coupling capability

opens the door to innovative solutions in intelligent medical devices, targeted therapy, and high-precision diagnostics [109]. This chapter synthesizes key recent advances to provide a systematic overview of the application landscape and future trajectory of ferroelectric materials in critical biomedical areas such as implantable bioelectronics, tumor treatment technologies, and neural engineering systems.

Traditional implantable electronic devices face the risk of requiring secondary surgery for removal because the inorganic piezoelectric ceramics and piezoelectric polymers currently used are generally not biodegradable. To address this challenge, Zhang et al. innovatively developed a biodegradable organic ferroelectric crystal 2, 2, 3, 3, 4, 4-hexafluoro-1, 5-pentanediol (HFPD) with a large piezoelectric response by organically combining ferro-electrochemistry with bioelectronics [110]. The authors used a hydrogen/fluorine substitution strategy and crystal engineering to emulate the β -phase PVDF structure, but reduced the structural units from thousands to only 3 $-\text{CF}_2-$ groups, forming an infinitely long chain structure through hydrogen bonding interactions. This design enables the HFPD's piezoelectric response d_{33} to reach 138 pC/N, catching up with the inorganic ceramic BTO, which is a four-fold improvement over traditional small molecule piezoelectric performance. It is worth noting that adjacent HFPD molecules form a 2D hydrogen bond network through $\text{O}-\text{H}\cdots\text{O}$ hydrogen bond interactions. This property makes HFPD crystals easily soluble in a variety of solvents (especially body fluids), thereby facilitating the degradation of the compound in the body. The study confirmed that the compound has good biosafety, biocompatibility, and biodegradability. Taking into account the brittleness and rigidity of the crystal, the team prepared an HFPD-polyvinyl alcohol flexible piezoelectric composite film with a d_{33} of 34.3 pC/N by solution evaporation. Based on this film, they assembled a controllable transient electromechanical device and confirmed that it has good biosensing performance. The biosafety and degradation experimental results are shown in Figure 12a. This research provides promising candidate materials for degradable implantable electronic medical devices and also provides molecular piezoelectric materials with important application outlets closely related to human health. This research provides an innovative solution to the biodegradability problem of implantable devices and is expected to greatly improve patients' quality of life. However, for truly practical transient implantable devices, biocompatibility and biodegradability of the materials are only the foundation; the synergy between “functional stability” and “controllable degradation” is crucial [108, 111, 112]. HFPD crystals achieve biodegradability in physiological environments through a 2D hydrogen bond network, providing a chemical basis for controlling their degradation rate (e.g., through the proportion of composite materials and coating design). Future research needs to systematically quantify the long-term degradation kinetics of these materials in dynamic physiological environments (such as pH fluctuations and the presence of enzymes) and establish a correlation model between degradation rate and piezoelectric performance decay. This will ensure the functional integrity of the devices during treatment and prevent premature failure or prolonged retention.

Ferroelectric materials have shown unique advantages in the field of tumor therapy, especially in inducing immunogenic cell death and activating the immune system. Du et al. designed and



complex tumor microenvironment (such as variable pH values and abundant biomolecule adsorption), ensuring the long-term stability of the material's surface properties and polarization state is crucial for maintaining the reliability of its "smart switch" function. At the same time, as an exogenous nanomaterial, its biosafety and ultimate metabolic pathways must be clearly defined: although this study demonstrates therapeutic efficacy, the long-term retention of the material and the potential impact of its degradation products on major organs still require comprehensive evaluation through more systematic *in vivo* toxicological and pharmacokinetic studies. This is an essential step for its eventual clinical translation.

Traditional implantable bioelectronic devices lack neuron-preferred properties, making it difficult to achieve efficient interface adaptation with neural tissue. To address this challenge, Wang et al. developed neuronal ferroelectric bioelectronic devices (FerroEs), which achieve seamless integration and adaptive communication with the nervous system by fusing the flexibility and topological structural properties of adaptive neurons with neuron-like behavior (Figure 12c) [36]. The authors designed a FerroE device with excellent mechanical flexibility and complex topological structure, enabling it to mimic the biological characteristics of neurons. The research results show that FerroE can not only generate a voltage of about 3.6 V within 100 ms, but also maintain excellent functional stability and biocompatible interface after 3 months of implantation in the body. FerroE devices bring new opportunities for the development of next-generation brain-computer interfaces and biomedical devices. Particularly in the fields of neural prosthetics and brain-computer interfaces, these devices, which seamlessly integrate with neural tissue, enable more natural and efficient information transmission, providing new technological approaches for the treatment of neurological diseases. The breakthrough significance of this research lies in the successful organic combination of the electrical properties of ferroelectric materials with the biological requirements of neural interfaces for the first time, solving the interface adaptation problem that has long plagued implantable neural devices. By simulating the characteristics and behaviors of neurons, FerroE devices can communicate with the nervous system more efficiently and naturally, laying a solid foundation for the future development of high-performance brain-computer interfaces and neural repair technologies.

4.5 | Applications and Challenges of Fe-OLETs in Optoelectronic Devices

Organic light-emitting transistors (OLETs) have broad application prospects in modern electronic and optoelectronic devices. Recently, ferroelectric materials have been attracting increasing attention as gate dielectrics in OLET devices, particularly ferroelectric-based OLETs (Fe-OLETs). The remanent polarization characteristics of ferroelectric materials allow for the modulation of charge injection, carrier recombination, and light emission under an electric field, thereby providing more efficient energy conversion and performance optimization in OLET devices. Fe-OLET, as an emerging optoelectronic device, has demonstrated its potential in non-volatile memory, low-power driving, and high-brightness light emission. For example, Xu et al. successfully developed an OLET with non-volatile memory

capabilities by employing ferroelectric organic crystals, achieving excellent synergistic effects between ferroelectric polarization and photoelectric conversion [114].

Although Fe-OLET shows strong potential for applications, its development still faces certain challenges. First, traditional OLET devices typically use materials with high dielectric constants as the gate dielectric, while the application of ferroelectric gates in these devices is still immature. Furthermore, although some studies have explored the potential of Fe-OLETs in achieving high-efficiency luminescence, current research mainly focuses on interface optimization and the development of new materials, and largely lacks in-depth analysis of device long-term stability and environmental adaptability. To this end, Wang et al. further investigated the optimization of microcavity structures to improve the light emission efficiency and color purity of OLETs, providing a new direction for Fe-OLETs [115]. In the future, with the synergistic optimization of ferroelectric materials and organic semiconductor materials, and the continuous progress in novel microstructure and interface design, the application prospects of Fe-OLET will become even broader.

5 | Limitations and Problems

Ferroelectric materials show immense potential in their journey toward large-scale applications, but they also face a series of profound technical bottlenecks. These challenges primarily lie in the core aspects of material physics, process integration, and device reliability, limiting their transition from laboratory research to industrial production.

First, there are issues concerning the reliability and performance degradation of ferroelectric thin films. The fatigue mechanism primarily originates from the repeated electrical cycling, where charges are injected at the interface and trapped by defects, forming a screening electric field. Simultaneously, defects such as oxygen vacancies migrate and aggregate, pinning domain walls and hindering polarization reversal, leading to a continuous decrease in reversible polarization charge. The microscopic mechanism is closely related to the aforementioned charge injection, trap formation, and the migration and aggregation of defects at the ferroelectric/electrode interface. For HfO₂-based ferroelectric materials, although they have high CMOS compatibility, the metastable phase characteristics of the thin film, grain size, and interface defects exacerbate the fatigue process, significantly affecting their fatigue and retention performance, which is a core challenge in current process optimization. On the other hand, to achieve low-power operation, the ferroelectric layer needs to be continuously thinned, which increases the risk of tunneling leakage and premature breakdown. Thin film uniformity, grain boundary quality, and the integrity of the electrode interface barrier are decisive factors. Especially in ferroelectric tunnel junctions, pinhole defects in the ultra-thin ferroelectric layer can directly lead to device short circuits or unstable resistance states.

Intrinsic and process stability challenges of low-dimensional and novel materials. For 2D van der Waals ferroelectric materials, despite the advantages of atomic-level thickness and intrinsic flexibility, their stability faces a dual challenge: intrinsic environmental stability and ferroelectric phase stability. Controllable

preparation and transfer techniques for large-area, uniform, and high-quality single-crystal thin films are still immature, leading to significant device performance variations and making uniform integration difficult. Although organic-inorganic hybrid and molecular ferroelectric materials show greater promise in catalytic and flexible sensing applications, their chemical stability (resistance to moisture, heat, and radiation) and mechanical strength are generally poor. They are prone to degradation under long-term or harsh operating conditions, severely limiting their practical applications.

The complexity of device integration and large-scale manufacturing presents significant challenges. Whether integrating ferroelectric thin films with silicon-based CMOS, wide-bandgap semiconductors, or flexible substrates, interface issues remain a core challenge. Lattice mismatch, differences in thermal expansion coefficients, interdiffusion, and interfacial chemical incompatibility introduce defect states, severely degrading device performance and reliability. Ferroelectric properties are extremely sensitive to the crystal orientation, stress state, and defect density of the thin film. Achieving high uniformity of ferroelectric thin film performance on large-sized wafers at the nanoscale is a prerequisite for mass production, which places extremely high demands on the precise control of deposition and annealing processes.

The problem of ferroelectric properties and multi-physical field coupling. In many applications, ferroelectricity is not the only required property. For example, catalysis requires a highly active surface, photovoltaics require a narrow band gap, and sensors require high flexibility. Optimizing one performance parameter often comes at the expense of others, requiring complex material compositions and structural designs to achieve a balance.

In the biomedical field, there is a conflict between material performance and biological safety [116–118]. Biomedical applications require materials that not only function effectively in the short term but also coexist harmoniously with living tissues over the long term [119, 120]. This involves both functional stability and structural compatibility. First, the ferroelectric/piezoelectric properties of the material must remain stable over the long term in a dynamic physiological environment, without undergoing significant degradation. Second, the device needs to possess excellent mechanical flexibility and a matching micro topological structure to minimize mechanical damage to the tissue and actively guide cell (such as neuron) adhesion and integration, while inhibiting fibrous encapsulation. Furthermore, for biodegradable materials, the degradation rate must match the tissue repair cycle, and the degradation products must be non-toxic and metabolizable. On the other hand, transforming materials into effective implantable devices presents both engineering and biological challenges. A key challenge is how to continuously, stably, and wirelessly power implantable devices. Current research explores the use of external fields such as light and ultrasound to achieve wireless energy conversion and signal modulation. At the same time, technical challenges such as miniaturization, flexible packaging, and stable electrode-tissue interfaces also need to be addressed. The most fundamental challenge lies in how to translate the physical signals (electrical, mechanical, and thermal) generated by ferroelectric materials into precise, controllable, and efficient biological functions (such

as inhibiting specific neuronal activity to treat heart disease). This requires more fundamental and in-depth research into the complex interaction mechanisms at the device-biological interface.

Therefore, the future development of ferroelectric materials requires deep integration and collaborative innovation across multiple disciplines, including materials science, microelectronics engineering, physics, and biomedicine.

6 | Conclusion and Outlook

Research on ferroelectric materials has progressed substantially, transitioning from fundamental property exploration to diverse functional applications. Recent advances in synthesis techniques and characterization tools have enabled a series of breakthroughs across multiple fronts. In terms of performance tuning, strategies have evolved from conventional composition design toward cross-scale optimization—encompassing atomic-scale defect engineering, nanoscale domain configuration, and macroscale heterointerface control. Multi-field coupling (e.g., light, electricity, stress, and heat) has emerged as a pivotal research direction, allowing dynamic modulation of ferroelectric behaviors via external stimuli for on-demand property tailoring.

Application-wise, ferroelectrics have moved beyond classical memory and sensing uses to demonstrate great potential in cutting-edge fields such as high-density data storage, energy harvesting and conversion, and intelligent catalysis. Emerging areas—including ferroelectric-enhanced catalysis, piezoelectric nanogenerators, and neuromorphic computing—are progressing with particular momentum.

Nevertheless, several challenges remain to be addressed:

First, at the basic research level, key scientific issues such as the dynamic evolution mechanism of ferroelectric domain walls, the limiting speed of polarization reversal, and the phase transition dynamics under multi-field coupling conditions are still unclear and need to be further revealed with the help of in situ characterization technology and theoretical simulation.

Second, in terms of performance control, there are still difficulties in achieving the coordinated optimization of key parameters such as the coercive field, residual polarization intensity, and piezoelectric coefficient of ferroelectric materials, especially overcoming the mutual constraints between material properties (such as the contradiction between a high piezoelectric coefficient and a low dielectric loss).

Third, in terms of material preparation, technical challenges such as the controllable preparation of large-area, high-quality ferroelectric thin films, the large-scale synthesis of low-dimensional ferroelectric materials, and the precise control of heterojunction interface defects have not yet been fully resolved.

Fourth, in terms of device applications, ferroelectric devices are subject to problems such as fatigue and aging failure (polarization reversal durability), performance stability in high-temperature environments, and compatibility with existing semiconductor

processes, which restrict their practical application. Furthermore, emerging applications (such as flexible electronics and bio-implants) place new demands on materials, such as stretchability and biocompatibility.

Future research will require interdisciplinary collaboration, combining artificial intelligence and machine learning methods to accelerate the development of new materials, develop in situ real-time characterization techniques to analyze materials' dynamic behavior, and explore new phenomena combining ferroelectric materials with topological states and quantum effects, with the goal of breaking through existing performance bottlenecks and opening up new application areas. The future of ferroelectric materials lies in the continued fusion of materials science, physics, chemistry, and engineering. By addressing these challenges and exploiting the unique coupling properties of ferroelectric materials, we can envision the emergence of smarter, more efficient, and more adaptable technologies that will play a central role in the development of flexible electronics, artificial intelligence, and sustainable energy systems.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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