
Review

Defect-mediated switching and interfacial charge transport in advanced ferroelectric components

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Abstract: Ferroelectric materials are central to advanced electronic components, yet their performance and reliability cannot be inferred from polarization magnitude, crystal phase, or nominal composition alone. In real devices, the functional response is carried by a field-driven operating state in which switchable polarization interacts with defect landscapes, interfacial screening, trapped charge, leakage pathways, domain-wall dynamics, and cycling-induced degradation. This review frames advanced ferroelectric components from a solid-state and materials-physics perspective, focusing on defect-mediated switching and interfacial charge transport as coupled determinants of function. The discussion connects switching kinetics, oxygen-vacancy migration, defect dipoles, internal bias, wake-up, fatigue, imprint, finite screening length, band bending, charge injection, trap-assisted conduction, nonideal hysteresis, and microstructural constraints across capacitors, ferroelectric field effect transistors (FeFETs), ferroelectric tunnel junctions, sensors, actuators, energy harvesters, and flexible components. Particular emphasis is placed on separating reversible ferroelectric switching from charge-assisted electrical response, conductive hysteresis, interfacial drift, and leakage-limited behavior. A central contribution is an evidence hierarchy for ferroelectric component claims, distinguishing polar identity, switchable ferroelectricity, interface-controlled switching, trapped-charge response, leakage and conduction mechanisms, domain-wall contribution, and device- and reliability-level functionality. This framework positions reliability as the time-dependent expression of the coupled switching–interface–transport state rather than as a final metric detached from materials physics. By linking functional output to the physical state that carries it, the review provides a transferable basis for evaluating and comparing ferroelectric materials in advanced electronic components.

Keywords: ferroelectric materials; advanced electronic components; defect-mediated switching; interfacial charge transport; charge trapping; leakage pathways; domain-wall dynamics; reliability

1. Introduction

Ferroelectric materials have evolved from model polar solids into active components for switching, charge storage, interfacial modulation, sensing, actuation, and electromechanical conversion under repeated operation. Their functionality derives from a field-addressable order parameter, but the practical response of a component is rarely determined by polarization alone [1]. Once incorporated into thin films, electrode-coupled stacks, semiconductor-integrated architectures, multilayers, or ceramic elements, the electrically accessible polar state is constrained by defects, interfaces, charge transport, domain-wall dynamics, domain-wall motion, and electrical boundary conditions [2].

Traditional descriptors such as remanent polarization, coercive field, dielectric constant, piezoelectric coefficient, crystal phase, and nominal composition remain useful, but they do not fully determine component behavior. A material with a favorable polar phase may suffer from leakage, imprint, fatigue, or poor retention [3]. A stack with a wide memory window may contain a substantial trapped-charge contribution. A ceramic with a strong electromechanical response may degrade through defect pinning or grain-boundary losses [4]. A tunnel junction with high resistance contrast may depend on defect-assisted transport rather than polarization-controlled barrier modulation [5]. These cases point to the same underlying issue: the measured function is carried by an operating state, not by an isolated material descriptor.

Switching is central to that operating state. In real ferroelectric components, polarization reversal proceeds through nucleation, domain-wall motion, local field redistribution, and defect-sensitive kinetics [6]. Defect dipoles, oxygen vacancies, charged traps, nonstoichiometry, and mobile ionic species can stabilize the polar phase, assist wake-up, shift internal bias, immobilize walls, accelerate leakage, or seed fatigue. The same defect population may be enabling at one stage of operation and limiting at another [7]. Component performance, therefore, depends on whether defects remain compatible with reversible switching under field, time, temperature, and cycling [8].

Interfaces impose an equally strong constraint. Electrode/ferroelectric and ferroelectric/semiconductor boundaries define screening efficiency, depolarization fields, barrier profiles, band bending, charge injection, and trap occupancy [9]. These interfacial conditions control the stability of written polarization states, the magnitude and retention of memory windows, tunneling electroresistance (TER), leakage onset, and threshold-voltage drift. In nanoscale components, the interface may dominate the usable response more strongly than the nominal bulk ferroelectric layer [10]. The polar state that matters is, therefore, the one stabilized by the stack, not the one inferred from the ideal crystal.

Charge trapping and leakage further complicate interpretation. Hysteresis, resistance modulation, threshold shifts, and electromechanical response may contain contributions from reversible switching, capacitive charging, injection, detrapping, ionic redistribution, dielectric relaxation, and conductive pathways [11]. Treating all hysteretic responses as ferroelectric switching weakens both the mechanism and reliability claims. A physically credible interpretation must separate switchable polarization from charge-mediated artifacts while recognizing that, in working components, these processes often coexist and interact [12].

The need for a compact materials-physics framework is especially clear across ferroelectric random-access memory (FeRAM) and ferroelectric capacitor (FeCAP) elements [13], ferroelectric field-effect transistors (FeFETs), ferroelectric tunnel junctions (FTJs), sensors, actuators, energy harvesters, and flexible ferroic components [14].

In this review, advanced ferroelectric components are examined through defect-mediated switching and interfacial charge transport. The objective is not to catalog ferroelectric families or device classes but to establish a transferable framework for judging when a response is genuinely switchable, interface-controlled, trap-mediated, leakage-limited, domain-wall-assisted, or reliable at the component level.

2. Switching as a defect-sensitive ferroelectric process

Ferroelectric switching is often represented as a reversible inversion of polarization, but in functional components, it is better read as a field-driven kinetic process constrained by defects, interfaces, elastic boundary conditions, and local charge redistribution [15]. The polar state does not reverse through a homogeneous rotation of dipoles across an ideal lattice. It evolves through nucleation, growth, wall motion, pinning, depinning, and stabilization of domains under an applied field. The measured switching response is therefore a convolution of intrinsic lattice instability, domain-wall dynamics, defect redistribution, leakage, and interfacial screening [16].

Coercive field, remanent polarization, and loop shape remain useful descriptors only when they are interpreted within this kinetic landscape. A lower coercive field may indicate easier domain-wall motion, but it may also reflect charge injection, defect-assisted nucleation, local field concentration, or partial screening of depolarization fields [17]. A larger remanent polarization may indicate stronger switchable order, but it may also be affected by leakage correction, incomplete saturation, built-in bias, or nonuniform field distribution [18]. In advanced components, switching parameters become physically meaningful only when their evolution with field amplitude, pulse width, frequency, temperature, cycling, and device geometry is internally consistent.

Quantitative switching kinetics can be resolved through two limiting descriptions. The Kolmogorov–Avrami–Ishibashi (KAI), or Ishibashi–Orihara, formalism expresses the switched fraction as Eq 1:

$$f_{sw} = 1 - \exp[-(t/\tau)^n] \quad (1)$$

where f_{sw} is the switched fraction, t is time, τ is a characteristic reversal time, and n is an effective exponent associated with the nucleation-and-growth process under an approximately homogeneous field [19]. In geometrically constrained films, n should not be interpreted automatically as a literal domain-growth dimensionality. Defect-rich polycrystalline layers frequently exhibit broad or asymmetric switching-current transients that cannot be represented by a single τ . The nucleation-limited switching (NLS) framework instead treats the capacitor as an ensemble of independently switching regions whose local waiting times are distributed by spatial variations in activation field, grain orientation, defect density, interfacial screening, and domain-wall pinning [20]. In HfO₂-based metal–ferroelectric–metal capacitors, NLS behavior has been resolved over five orders of pulse width and connected with the retention kinetics of the written state [21]. Discrimination between KAI and NLS therefore requires field- and temperature-dependent transients acquired over a sufficiently

broad time window; agreement over a restricted interval does not establish a unique microscopic switching mechanism.

Defects influence switching at several levels. Point defects, defect dipoles, dopant-vacancy complexes, oxygen vacancies, cation disorder, and charged traps can modify local polarization stability, change nucleation barriers, pin domain walls, and introduce internal fields [22]. The relevant variable is not the presence of defects alone but their charge state, mobility, spatial distribution, interaction with domain walls, and evolution under repeated electrical loading [23].

At the atomic scale, the influence of a point defect is determined by its chemical identity, charge state, crystallographic site, and position relative to the local polarization texture. The associated changes in bond lengths, cation–anion displacements, local coordination, and electrostatic potential reshape the switching-energy landscape rather than producing a uniform increase or decrease in coercivity. *Ab initio*–based simulations show that point defects generate site-dependent changes in domain-wall stability and mobility, thereby modifying the local pathway through which polarization reversal propagates [24]. The macroscopic switching response, therefore, reflects not only defect concentration but also the atomic configuration through which each defect couples to the polar lattice.

Oxygen vacancies are especially consequential in oxide ferroelectrics. Their migration under the electric field can redistribute local charge, compensate polarization, alter Schottky barriers, and form internal bias fields. Vacancy accumulation near electrodes, grain boundaries, or domain walls can assist nucleation in early cycling and later suppress reversible switching through pinning or enhanced leakage. This dual role is central to wake-up and fatigue phenomena in several ferroelectric thin films and capacitors [25]. Wake-up can arise when field cycling redistributes defects into a configuration that releases pinned domains or reduces internal bias. Fatigue develops when repeated switching creates irreversible trapping, defect clustering, interfacial degradation, or domain-wall immobilization [26,27].

Defect dipoles introduce another switching constraint. In acceptor-doped or nonstoichiometric ferroelectrics, coupled defect complexes can align with the spontaneous polarization and generate aging or internal bias. At the atomic scale, the defect complex couples a local electric dipole and an associated lattice distortion to the spontaneous polarization. Its orientation modifies the relative stability of neighboring polar configurations, while local symmetry breaking and strain alter the atomic displacement pattern responsible for polarization and electrostrain [28]. Their reorientation under field may lag behind domain reversal, producing asymmetric hysteresis, time-dependent recovery, and field-history-dependent switching. Such behavior is not merely a material imperfection; it is part of the operational physics of the component. A stable ferroelectric state may require defect alignment, while rapid and reversible switching may require defect configurations that do not overconstrain domain-wall motion [29].

Bulk perovskite ceramics further show that point-defect control cannot be separated from phase stability and microstructural evolution. In $\text{BiFe}_{1-2x}\text{Ti}_x\text{Zn}_x\text{O}_3$, Ti–Zn incorporation modified the lattice parameters, promoted R3c/P4mm phase coexistence, reduced the average grain size from approximately 624 to 221 nm, and increased the remanent polarization from 0.058 to 0.863 $\mu\text{C}/\text{cm}^2$ [30]. The enhanced response was associated with the combined modification of Fe-related defect chemistry, oxygen-vacancy effects, crystal symmetry, and grain-scale switching conditions. A dopant-induced increase in remanence should therefore be interpreted as a coupled defect–phase–microstructure outcome rather than as evidence of a single isolated mechanism.

Switching is also shaped by the electrical boundary conditions imposed by the component stack. Electrodes, semiconductor contacts, dielectric interlayers, dead layers, and finite screening lengths create nonuniform fields that determine where domains nucleate and how switching fronts propagate [31]. The same ferroelectric material can therefore display different switching kinetics in a bulk ceramic, a metal-ferroelectric-metal capacitor, a ferroelectric-semiconductor stack, or a tunnel junction [32].

The microscopic carrier of polarization reversal also changes across material families. In wurtzite ferroelectric heterostructures, switching does not map directly onto the ferroelastic-domain processes common in many perovskites. In AlN/AlScN and related stacks, antipolar nuclei initiated in the ferroelectric layer and the elastic and electric fields of an advancing domain wall can reduce the reversal barrier across an internal interface, enabling polarization propagation into an adjacent polar but nominally non-ferroelectric layer [33]. Relaxor perovskites represent a different limit, in which the field response is distributed among polar nanoregions, domain reorientation, and field-induced phase transformations. In quenched $\text{Na}_{0.5}\text{Bi}_{0.5}\text{TiO}_3\text{--NaNbO}_3$ ceramics, in situ synchrotron diffraction linked the enhanced electromechanical response and cycling stability to an electric-field-induced cubic-to-rhombohedral transformation and the formation of a textured polar state [34]. A transferable switching framework must therefore identify the specific defect, interface, domain, or phase entity that carries polarization reversal in each material family.

In polycrystalline ceramics and textured films, microstructure adds a further kinetic filter [35]. Grain orientation, grain-boundary barriers, residual strain, porosity, secondary phases, and local compositional fluctuations distribute switching fields across the material [36]. Domain reversal becomes spatially heterogeneous, with some regions switching readily and others remaining pinned or only partially reoriented [37].

Processing history fixes the initial phase, stress, and defect landscape through which polarization reversal proceeds. Deposition technique, precursor or plume chemistry, oxygen chemical potential, substrate temperature, growth rate, and film thickness regulate stoichiometry, grain development, texture, residual stress, and the relative stability of competing structures. The relevant processing variables are material-specific. In sol-gel-derived lead zirconate titanate (PZT) films, the annealing atmosphere selects perovskite or residual pyrochlore content, crystallographic orientation, domain-pinning-center concentration, and ferroelectric response [38]. In sputtered AlScN, high-temperature annealing interacts with bottom-electrode texture, residual stress, interfacial coherency, and defect generation, thereby modifying the switching barrier and coercive field or, under severe conditions, producing structural damage before polarization reversal [39]. In hafnium zirconium oxide (HZO), mechanical confinement by the top electrode during crystallization inhibits out-of-plane expansion, suppresses equilibrium monoclinic-phase formation, and retains a larger metastable orthorhombic fraction [40]. The electrically tested component, therefore, begins from a processing-selected metastable state rather than from a uniquely composition-defined structure.

Capacitor area and electrode geometry introduce statistical, circuit-level, and electrostatic size effects that cannot be removed unconditionally by normalizing charge or current by area. A larger electrode samples more grains, nucleation sites, defect clusters, and weak leakage regions, whereas lateral downscaling increases the perimeter-to-area ratio and the relative contribution of edge fields, processing damage, and electrode-boundary inhomogeneity. In $\text{Pb}(\text{Nb,Zr,Ti})\text{O}_3$ (PNZT) and $(\text{Pb,L a})(\text{Zr,Ti})\text{O}_3$ (PLZT) thin-film capacitors spanning $13\text{--}9600\ \mu\text{m}^2$, the maximum switching current and apparent switching time depend on capacitor area and measurement-circuit elements, whereas the extracted activation field remains independent of both variables [41]. Geometry can remain

decisive even at nominally equal area: PZT ribbon capacitors with a substantially larger perimeter exhibit a stronger temperature- and field-dependent activation response than square capacitors, together with an additional trap contribution attributed to chemically reduced plasma-etched edges [42]. Area-dependent switching distributions, leakage, variability, and reliability must consequently be evaluated through active-area and perimeter scaling, together with the temporal resolution and detection limit of the measurement circuit.

Defect-mediated switching should therefore be treated as the operating state of ferroelectric components, not as a deviation from ideal ferroelectricity [43]. The functional question is whether the polar state can be written, retained, erased, and cycled while defects, interfaces, leakage paths, and domain walls remain compatible with reversible switching [44]. Performance and reliability begin at this level: not with the existence of polarization but with the stability of field-driven polarization reversal in a defect-active, interface-constrained material. The transition from the initial multidomain state to field-driven switching illustrates the coupled evolution of domain reversal and defect redistribution (Figure 1a,b) while continued cycling can modify domain accessibility and internal bias, giving rise to the distinct wake-up, imprint, and fatigue responses summarized in Figure 1c.

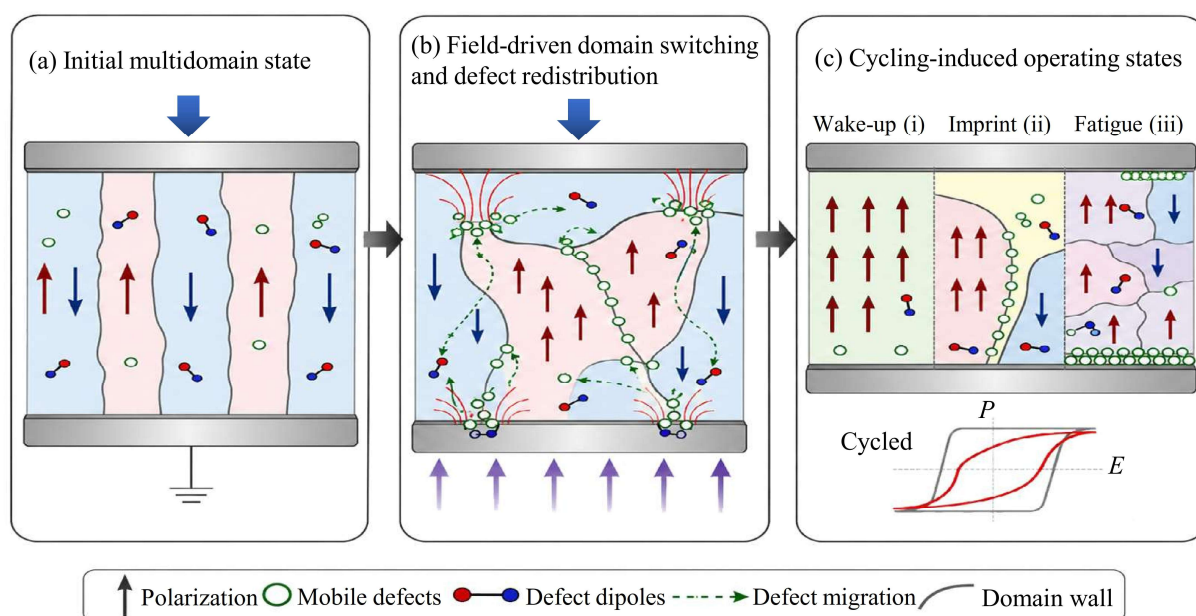


Figure 1. Defect-mediated switching in advanced ferroelectric components: (a) initial multidomain state; (b) field-driven switching and defect redistribution; and (c) cycling-induced operating states associated with: (i) wake-up, (ii) imprint, and (iii) fatigue.

3. Interfacial electrostatics and screening in ferroelectric stacks

The functional state of a ferroelectric component is set as much by its electrical boundary conditions as by the polar phase itself [45]. Once a ferroelectric layer is placed between electrodes, coupled to a semiconductor, inserted into a tunnel barrier, or integrated with dielectric interlayers, polarization is no longer governed only by bulk free energy. It is constrained by screening length, contact asymmetry, interface traps, band offsets, injected charge, and depolarization fields [46]. The component does not operate as a ferroelectric bulk with external contacts attached to it; it operates as a stack in which polarization and interface electrostatics are mutually constrained.

Incomplete screening is the first interfacial limitation. Bound charge associated with polarization must be compensated by free carriers, trapped charge, ionic defects, adsorbed species, or structural reconstruction [47]. Metallic electrodes screen more efficiently than semiconducting or dielectric interfaces, but even nominally metallic contacts introduce finite screening lengths, chemical bonding effects, and dead-layer-like regions [48]. These interfacial regions can increase the depolarization field, destabilize remanent polarization, favor backswitching, and modify the apparent coercive voltage. In ultrathin films, the interface can become comparable in importance to the ferroelectric volume itself [49].

Band bending translates interfacial electrostatics into charge transport. At electrode–ferroelectric and semiconductor–ferroelectric boundaries, work-function mismatch, polarization charge, defect states, and local stoichiometry determine barrier height, depletion width, carrier injection, and built-in field direction [50].

Ferroelectric–semiconductor interfaces are especially sensitive to this coupling. Polarization can modulate channel charge, shift threshold voltage, and define memory states, yet the same interface may host traps, dangling bonds, oxide defects, charge reservoirs, and chemical disorder that store charge independently of ferroelectric switching [51]. In such stacks, the memory window is a composite electrical quantity. It may contain remanent polarization, trapped charge, interface-state occupancy, mobile ions, and semiconductor depletion. Stability depends on whether polarization-induced modulation remains dominant over trap-assisted drift and charge relaxation [52].

Asymmetric boundary conditions introduce built-in fields and imprint. Different electrodes, unequal interfaces, graded composition, strain gradients, oxygen-vacancy accumulation, or interfacial dipoles can shift the energy balance between polarization states [53]. The result may be preferential switching direction, shifted hysteresis, retention asymmetry, or incomplete erase behavior. Imprint is therefore not only a degradation metric; it is an interfacial electrostatic signature of how the stack stores internal bias [54]. Its origin may lie in defect dipoles, trapped charge, asymmetric screening, or interfacial chemical reconstruction, and these contributions can coexist during cycling.

Charge injection further complicates polarization stability. Under high field, carriers may cross Schottky barriers, tunnel through thin layers, hop through traps, or accumulate at defect-rich interfaces [55]. The injected charge can screen polarization transiently, alter local fields, reduce apparent coercive voltage, or stabilize a written state that is not purely ferroelectric. During retention, the same charge may relax, redistribute, or become trapped, producing time-dependent loss of memory contrast. The stability of the polar state is therefore tied to the kinetics of interfacial charge exchange as much as to the intrinsic ferroelectric energy landscape [56].

Dead layers and passive interfacial regions are particularly damaging when they introduce capacitance mismatch or local field concentration [57]. A thin low-permittivity or non-switching layer can increase the effective depolarization field inside the ferroelectric, reduce the usable voltage across the switchable region, and amplify leakage at defects or roughness points. In capacitors, this may appear as reduced remanence, broadened switching, slanted loops, or premature fatigue. In tunnel junctions, the same interfacial layer may dominate barrier shape and tunneling electroresistance [58]. The nominal ferroelectric thickness becomes less informative than the effective electrostatic thickness of the full stack.

The microscopic origin and function of an interfacial layer are strongly material-dependent. In ScAlN/GaN heterostructures, atomic-resolution microscopy, spectroscopy, and first-principles analysis associate the interfacial nonswitching region with nitrogen-vacancy enrichment and compressive strain. These coupled perturbations increase the local switching barrier, leakage, and

breakdown susceptibility, thereby suppressing polarization reversibility near the interface [59]. Perovskite oxide interfaces can also be used constructively. In $\text{BiFeO}_3/\text{SrTiO}_3/\text{BiFeO}_3$ bilayers, control of the atomic termination and polar discontinuity stabilized distinct head-to-head and tail-to-tail configurations and predetermined the as-grown polarization orientation [60]. The interface can therefore either suppress switching through defect–strain coupling or select the polar state through atomic-layer electrostatics.

Interface chemistry also determines long-term reliability. Oxygen exchange with electrodes, interdiffusion, redox reactions, local amorphization, and field-driven vacancy redistribution can change screening and barrier properties during operation [61]. A stack that initially supports stable switching may evolve toward higher leakage, stronger imprint, reduced retention, or fatigue as interfacial states accumulate. These changes are often gradual, field-history dependent, and difficult to separate from bulk defect motion. The operative interface is therefore a dynamic electrostatic boundary, not a fixed structural plane defined at fabrication [62].

The polarization-controlled interfacial state is therefore not static: its electrostatic configuration establishes the operating boundary condition of the stack (Figure 2a–c), while its evolution with time and electrical history can appear as loss of retained state and internal-bias development or as injection- and asymmetry-related contributions to the measured response (Figure 2d).

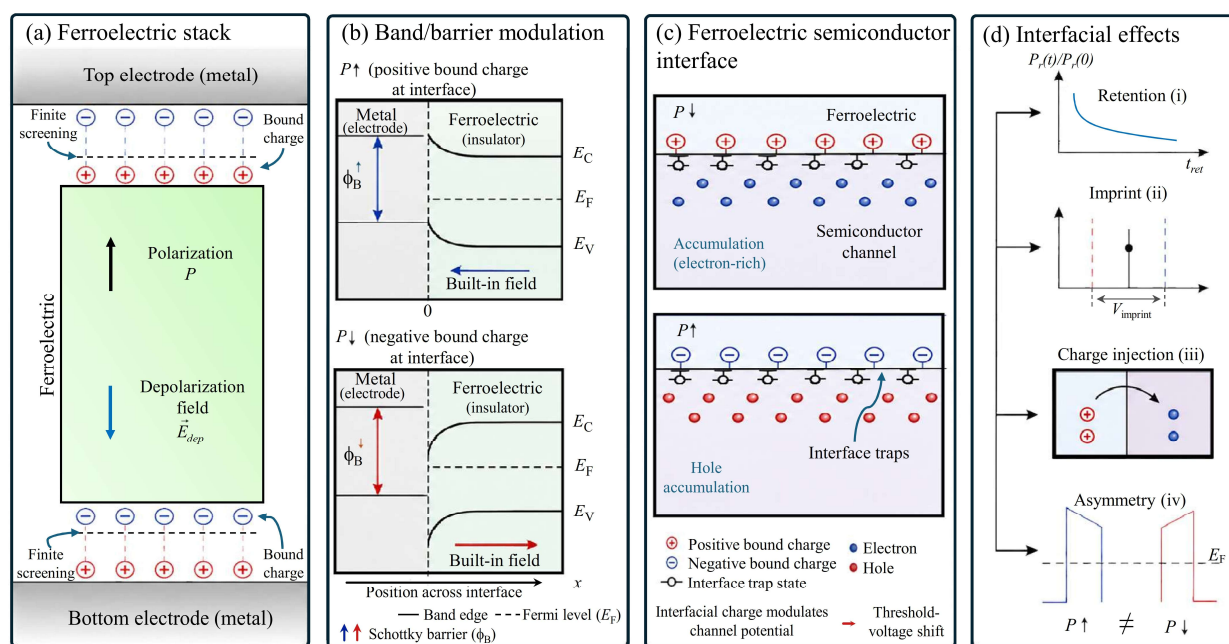


Figure 2. Interfacial screening and charge transport in ferroelectric stacks: (a) ferroelectric stack; (b) band/barrier modulation; (c) ferroelectric semiconductor interface; and (d) interfacial effects: (i) retention, (ii) imprint, (iii) charge injection, and (iv) asymmetry.

3.1. Two-dimensional van der Waals ferroelectrics as a distinct defect–interface regime

Two-dimensional van der Waals ferroelectrics define an interfacial regime that differs fundamentally from epitaxial and polycrystalline three-dimensional oxides. In conventional oxide films, polarization stability and reversal are constrained by substrate clamping, misfit strain, grain

boundaries, chemically bonded electrode interfaces, finite screening, passive layers, and oxygen exchange. Weak interlayer bonding in van der Waals crystals generally reduces mechanical constraint from the supporting substrate and permits atomically abrupt interfaces with fewer unsatisfied bonds. These characteristics can preserve polar order at thicknesses where conventional films become strongly affected by structural nonuniformity or dead-layer capacitance. They do not eliminate interfacial control: stacking registry, twist angle, interlayer spacing, local strain, surface contamination, encapsulation, and contact-induced disorder become primary variables governing the polar-domain configuration and its switching pathway [63].

The semiconductor character of α - In_2Se_3 couples polarization reversal directly to electronic transport. Atomic-resolution measurements show that the stacking sequence selects the orientation and direction of domain-wall motion: 2H- and 3R-stacked structures exhibit different switching pathways and markedly different electrical hysteresis. Defect-rich regions produced at evaporated metal contacts can generate polarized interfacial dipoles, stabilize poorly switchable domains, and impede domain-wall propagation. Polarization-controlled barrier modulation must therefore be distinguished from contact-induced defect states, nonuniform carrier injection, and stacking-dependent wall kinetics when interpreting resistance switching in α - In_2Se_3 junctions [64]. Monolayer In_2Se_3 further exhibits boundary-type-dependent, stepwise domain motion under local electric fields, demonstrating that defect sensitivity depends on domain topology and atomic registry rather than on defect concentration alone [65].

Point defects acquire an additional role when the ferroelectric layer is itself the semiconducting transport channel. Calculations for monolayer α - In_2Se_3 identify site-dependent selenium vacancies whose electronic character changes with polarization orientation. A vacancy can generate intrinsic n-type conductivity, modify defect-level depth, stabilize the ferroelectric phase, and alter the transition toward the paraelectric state, establishing a direct polarization–defect–conductivity coupling [66]. Bi_2SeO_5 extends this low-dimensional regime to a van der Waals ferroelectric oxide that retains robust polarization at monolayer thickness and forms atomically uniform interfaces with two-dimensional semiconductors [67]. Mechanistic assignments in these materials consequently require layer-number and phase identification, stacking and interface characterization, contact and encapsulation controls, defect-sensitive analysis, and transport measurements acquired under matched polarization and bias-history conditions.

4. Charge trapping, leakage pathways, and nonideal hysteresis

Electrical hysteresis in ferroelectric components is rarely a single-phenomenon response [68]. The measured charge, current, polarization, or resistance state may contain reversible domain switching, capacitive charging, leakage conduction, carrier injection, trap filling, ionic motion, and interfacial relaxation within the same voltage cycle. This overlap is particularly severe in thin films, semiconductor-coupled stacks, tunnel junctions, and defect-rich oxides, where high fields and short transport lengths make the separation between switching and conduction intrinsically difficult [69].

Charge trapping modifies both the apparent and the real switching state. Traps at interfaces, grain boundaries, domain walls, disordered layers, oxygen-vacancy-rich regions, or semiconductor contacts can capture carriers during writing and release them during retention or readout [70]. Their occupation changes local fields, shifts coercive voltage, screens polarization, and alters the energy balance between polarization states. A trapped-charge contribution may stabilize a written state transiently, but

it can also generate drift, imprint, threshold-voltage instability, or apparent memory that does not scale with remanent polarization [71].

Optical excitation introduces an additional defect- and transport-sensitive control variable in semiconducting ferroelectrics and ferroelectric/semiconductor stacks. Visible-light exposure can modify the oxygen-vacancy population and thereby alter phase stability and local electromechanical response, as demonstrated by photoinduced vacancy patterning that increased the ferroelectric-phase fraction of $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2$ thin films [72]. Illumination can also change carrier generation, trap occupation, polarization-charge screening, band bending, and leakage. Wavelength-resolved measurements in photo-ferroelectric/graphene devices have revealed competition between photovoltaic screening under above-band-gap excitation and defect-mediated charge redistribution under lower-energy illumination, producing markedly different hysteresis and resistance contrast between remanent states [73]. Photon energy and intensity can therefore modify the apparent switching state and device output through coupled photocarrier and defect dynamics, so dark and illuminated responses should be treated as distinct operating states.

Leakage pathways define another level of nonideality. Injection-limited conduction, Schottky emission, Fowler-Nordheim tunneling, direct tunneling, trap-assisted tunneling, Poole–Frenkel transport, hopping conduction, space-charge-limited current, and ionic migration can each dominate under different field, temperature, thickness, and electrode conditions [74]. These mechanisms not only add parasitic current; they reshape local potential profiles and modify the field actually experienced by the switchable region. A device may appear to switch at a given applied voltage while the internal field is being redistributed by conductive channels or trapped charge [75].

The voltage supplied by the measurement circuit is not necessarily the voltage acting across the ferroelectric layer. An effective series resistance (R_S), arising from electrode sheet resistance, film–electrode contacts, interfacial passive layers, wiring, and source impedance, produces a transient voltage drop $R_S I(t)$, such that Eq 2:

$$V_{FE}(t) = V_{app}(t) - R_S I(t) \quad (2)$$

where $V_{FE}(t)$ is the voltage across the ferroelectric layer, $V_{app}(t)$ is the applied voltage, $I(t)$ is the current, and t is time. Together with the total device and parasitic capacitance (C_{tot}), this resistance defines an external circuit time scale as Eq 3:

$$\tau_{RC} = R_S C_{tot} \quad (3)$$

where τ_{RC} is the corresponding circuit time scale. When τ_{RC} , the excitation rise time, and the polarization-reversal time become comparable, the switching-current maximum can broaden or shift, the apparent coercive voltage can change, and frequency-dependent loop distortion can emerge without a corresponding modification of the microscopic switching barrier [76]. These effects are geometry-dependent: capacitance scales primarily with electrode area, whereas sheet, contact, interfacial, edge, and perimeter resistances follow different scaling relations. Intrinsic switching kinetics, therefore, require measurement or reconstruction of the voltage across the ferroelectric layer and systematic tests against excitation rise time, series or load resistance, frequency, and capacitor area.

Nonideal hysteresis becomes especially misleading when the loop shape is treated as self-evident proof. Open, slanted, rounded, pinched, or frequency-dependent polarization-electric field (P - E) loops may reflect incomplete switching, relaxor-like response, domain-wall pinning, leakage, injection, dielectric loss, or Maxwell–Wagner-type interfacial polarization [77]. A large remanent-like charge can

be produced by conductive displacement; a slim loop can result from partial switching or from suppressed conduction; an asymmetric loop may indicate imprint or asymmetric injection. The loop is a useful signature only when read with current transients, leakage analysis, pulse protocols, and field-history dependence [78].

Time scale is central. Ferroelectric switching, carrier trapping, detrapping, ionic migration, and dielectric relaxation occur over different kinetic windows, yet they may overlap in practical measurements [79,80]. Fast pulses can suppress some leakage contributions while missing slow domain processes or defect relaxation. Slow triangular waveforms can enhance apparent polarization by integrating conductive current. Frequency dispersion, pulse-width dependence, retention decay, and recovery after rest can reveal whether the measured state is tied to stable polarization or to mobile charge [81]. The decisive quantity is not only the switched charge but the persistence and reversibility of the state after parasitic relaxation channels have evolved.

Measurement protocols for separating switching and parasitic charge:

- Positive-up-negative-down (PUND) applies a positive switching pulse, a nominally non-switching positive pulse, a negative switching pulse, and a nominally non-switching negative pulse. Subtraction of the non-switching charge from the corresponding switching charge estimates the reversible switched contribution under the selected pulse amplitude, width, delay, and initial state [18]. The result is not intrinsically leakage-free: incomplete saturation, backswitching, imprint, asymmetric injection, and time-dependent trapping or ionic redistribution can make the switching and non-switching baselines inequivalent.

- Dynamic leakage-current compensation separates current components through measurements acquired at different voltage-sweep rates. It assumes that leakage is reproducible at a given instantaneous voltage, whereas capacitive and polarization-related currents vary with the voltage rate [78,79]. The correction loses physical validity when conduction depends on bias history, polarization state, trap occupancy, temperature drift, or ionic redistribution, or when switching kinetics differ across the selected sweep rates.

- Pulse-based switching protocols vary pulse polarity, amplitude, width, interpulse delay, and read conditions to resolve switching-current transients, non-switching charge, retention, recovery, and write-read asymmetry [80,81]. Their interpretation is restricted by the electrical bandwidth, the voltage actually established across the ferroelectric layer, pulse-induced read or write disturbance, and the temporal window sampled; processes occurring faster or slower than that window may remain unresolved.

- Bias-history analysis compares the electrical response after controlled pre-poling, dwell, rest, and voltage-sequence conditions. Dependence on prior bias and relaxation time can reveal internal bias, trapping/detrapping, backswitching, or mobile-charge redistribution [71]. Bias history does not identify the microscopic carrier uniquely and must be correlated with temperature, frequency, retention, stack asymmetry, or interface-sensitive measurements. Consistency among complementary protocols, rather than any single correction procedure, is required to support an intrinsic polarization-switching assignment.

Proton-doped NdNiO₃ capacitors provide an experimentally resolved case in which the dominant carrier of remanent response changes with field and measurement timescale. Pristine NdNiO₃ exhibits an elliptical resistive electric displacement-electric field (D - E) trajectory, whereas hydrogenation suppresses conductivity and produces a field-dependent remanent response. Double-wave or PUND subtraction resolves a switchable component, but the nominally non-switching baseline remains dependent on the preceding polarization state; circuit-based reconstruction consequently yields lower remanent polarization (P_r) values than direct subtraction. Below approximately 243 kV/cm, the

S-shaped $P_r(E)$ dependence was assigned to proton-involved dipole switching, whereas the exponential high-field increase was attributed to proton trapping through ionic hopping. The additional dependence on pulse duration and interpulse relaxation demonstrates that remanent charge is not a protocol-independent measure of stable ferroelectric polarization [82] (Figure 3).

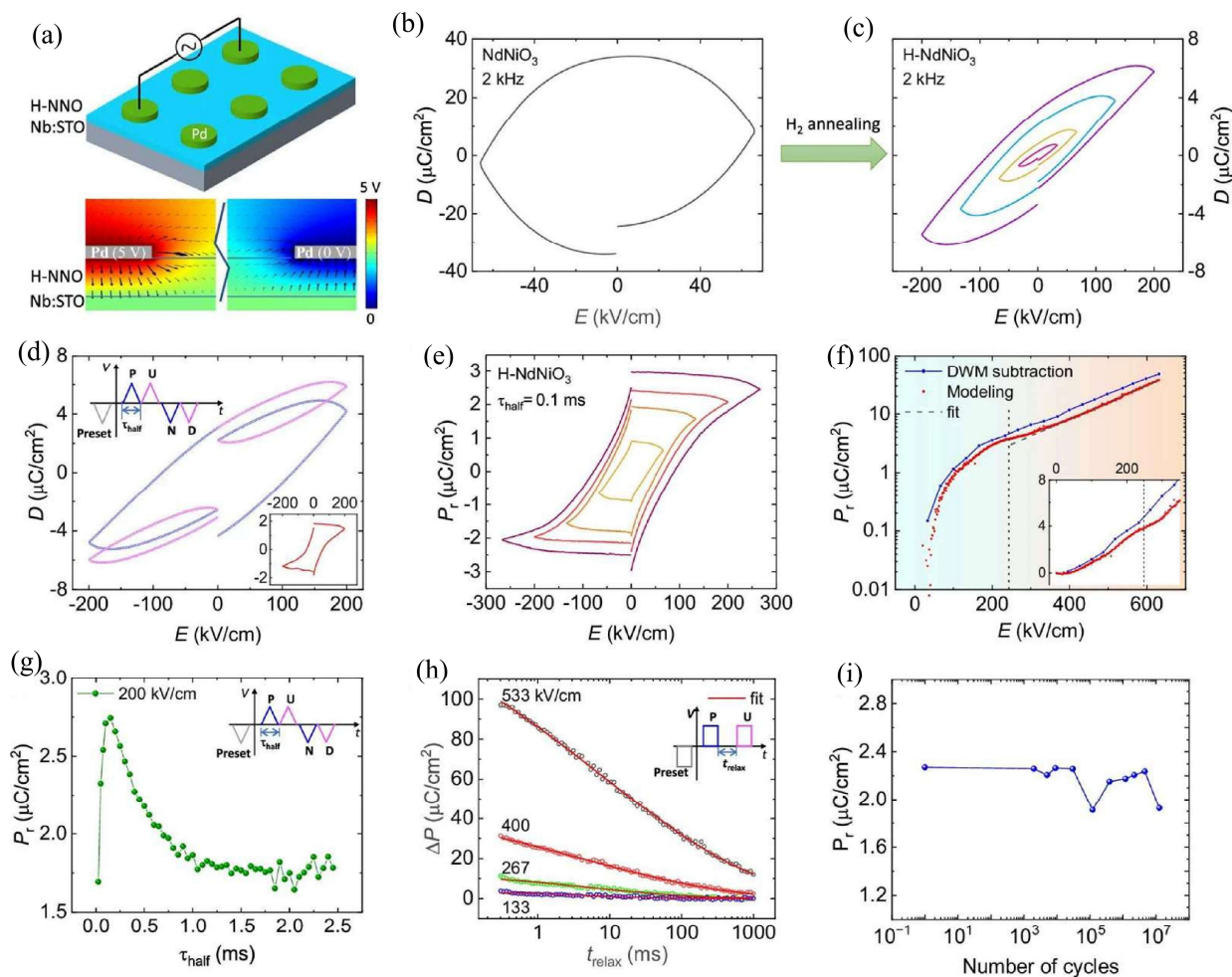


Figure 3. Field- and time-dependent separation of dipolar switching and space-charge polarization in hydrogenated NdNiO₃ capacitors. (a) Device geometry and simulated potential distribution; (b, c) D - E responses of pristine NdNiO₃ and hydrogenated NdNiO₃ measured at 2 kHz; (d) double-wave/PUND sequence, primary and secondary responses, and extracted differential loop; (e) PUND loops acquired at different maximum electric fields using a half-wave period of 0.1 ms; (f) remanent polarization obtained through direct PUND subtraction and circuit-based reconstruction; the exponential high-field regime was attributed to proton trapping through ionic hopping; (g) dependence of remanent polarization on half-wave period at 200 kV/cm; (h) relaxation of the polarization difference with interpulse delay; (i) PUND-derived remanent polarization during electrical cycling (Reproduced from Ref. [82] with permission).

Conduction analysis must remain consistent with stack physics. A fitted transport law is not sufficient when the extracted parameters are incompatible with electrode barriers, dielectric thickness, trap energies, temperature dependence, or known defect chemistry. Schottky-like behavior may mask

bulk-limited transport; Poole–Frenkel fits can be ambiguous in heterogeneous films; space-charge-limited conduction may coexist with injection barriers; and tunneling may be strongly modified by local defects and roughness [83,84]. In ferroelectric tunnel junctions and ultrathin capacitors, defect-assisted conduction can mimic polarization-controlled resistance modulation unless the barrier change is tied to the switching state [85].

Ionic motion is a persistent source of ambiguity. Oxygen vacancies, protons, mobile cations, and charged defect complexes can migrate under bias, particularly near interfaces and grain boundaries [62,86]. Their redistribution can create internal bias, stabilize conductive paths, modify barrier heights, or produce slow hysteresis that resembles ferroelectric memory. In oxide components, this ionic contribution may couple to genuine polarization reversal rather than simply replace it [87]. The difficulty is not the existence of mixed responses but the tendency to assign the full electrical signature to switching when part of the state is carried by mobile defects.

A physically useful interpretation separates reversible polarization, conductive charge flow, trapped charge, and ionic redistribution without pretending that they are fully independent [88]. In that picture, charge trapping and leakage are not residual corrections to ideal ferroelectricity; they are boundary conditions that decide whether switching can be used reliably. Charge trapping can redistribute local electrostatic conditions, while conductive and ionic pathways introduce field- and history-dependent charge transfer (Figure 4a,b). These contributions can shift the measured P_r and coercive field (E_c), away from values associated with reversible switching alone, as schematized in Figure 4c.

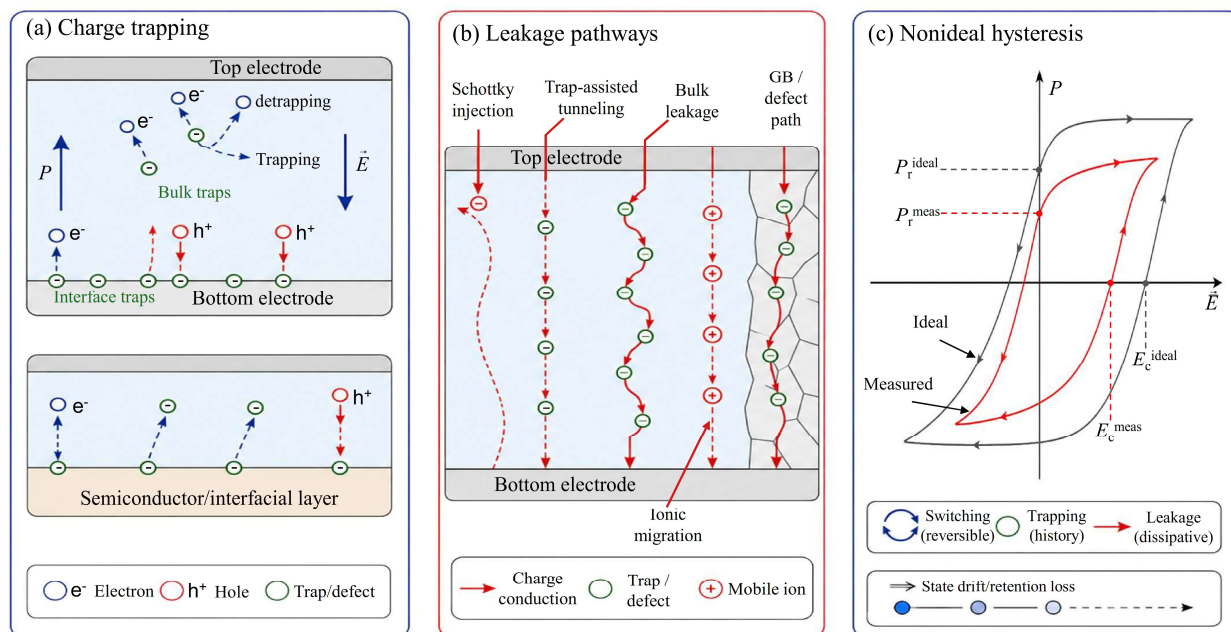


Figure 4. Charge transport and nonideal ferroelectric response: (a) charge trapping; (b) leakage pathways; and (c) nonideal hysteresis.

5. Domain walls and microstructural pathways in functional response

Domain walls provide one of the main channels through which ferroelectric components depart from an ideal lattice-centered response [89]. Their contribution is not limited to extrinsic enhancement of dielectric or piezoelectric coefficients. They participate in switching kinetics, field-induced strain, local dissipation, charge accumulation, and failure under repeated electrical or electromechanical loading [90]. A component with high polar order can still show limited functionality if its domain walls are immobilized, overpinned, electrically lossy, or disconnected from the field pathway imposed by the device geometry.

Wall mobility is governed by a balance between elastic compatibility, electrostatic cost, defect pinning, grain constraint, and local field distribution. Mobile walls can increase permittivity, soften electromechanical response, and support large-signal strain [91]. Strongly pinned walls can improve stability and reduce losses, but they can also suppress switchability and reduce reversible actuation. The functional optimum is not maximum mobility. It is a field-accessible wall population that contributes to response without driving excessive hysteresis, aging, or irreversible defect redistribution. Under subcoercive excitation, the field-amplitude dependence of the dielectric or piezoelectric response can be quantified through the Rayleigh relations Eq 4:

$$\varepsilon'(E_0) = \varepsilon_{init} + \alpha_\varepsilon E_0 \text{ and } d'(E_0) = d_{init} + \alpha_d E_0 \quad (4)$$

where E_0 is the amplitude of the applied subcoercive electric field, $\varepsilon'(E_0)$ and $d'(E_0)$ are the field-dependent dielectric permittivity and piezoelectric coefficient, respectively, ε_{init} and d_{init} are the corresponding field-independent terms, and α_ε and α_d are the dielectric and piezoelectric Rayleigh coefficients, respectively. The field-independent terms contain the intrinsic lattice response, together with reversible displacements of domain walls and other mobile interfaces, whereas $\alpha_\varepsilon E_0$ and $\alpha_d E_0$ quantify the irreversible contribution associated with depinning and displacement through a disordered energy landscape. This separation is physically meaningful only within a verified Rayleigh range, where the coefficients vary linearly with field amplitude, and the excitation remains below irreversible polarization reversal, field-induced phase transformation, and leakage-dominated response. A nonzero Rayleigh coefficient should therefore not be assigned automatically to domain-wall motion without consistency with harmonic, structural, microstructural, or field-history evidence [92].

Charged and neutral walls carry different physical consequences. Nominally neutral walls may contribute primarily through reversible motion and ferroelastic reconfiguration, while charged walls require electronic or ionic compensation and can become preferential sites for conduction, trapping, or local chemical instability [93]. BiFeO₃ provides a direct example of this coupling: charged-defect accumulation at domain walls can produce p-type hopping conduction, making wall transport dependent on local defect chemistry and thermal atmosphere rather than on wall polarity alone [94]. Conductive walls may therefore support localized transport, but they may also short-circuit a switching region, accelerate leakage, or concentrate degradation according to their connection to electrodes and the surrounding microstructure.

Defects and domain walls form a coupled kinetic landscape. Atomic- and nanoscale observations in BiFeO₃ show that defect ordering and wall decoration modify local potential and pinning, providing a direct link between defect configuration and domain-wall mobility [95]. More generally, oxygen vacancies, defect dipoles, aliovalent dopants, cation disorder, and trapped charges can produce analogous coupling in other ferroelectric families. During cycling, wall motion can also redistribute defects, open new trapping configurations, or drive local strain accumulation. Fatigue and imprint

often emerge through this reciprocal coupling: the wall structure changes the defect landscape, and the evolving defect landscape changes the wall response [96].

Dislocations constitute an extended-defect pathway distinct from point defects and grain boundaries. Their elastic fields perturb local polarization, modify domain-nucleation barriers, and create preferred pinning or depinning configurations for domain walls. The resulting response depends on dislocation line orientation, Burgers vector, density, and geometric relation to the wall. In BaTiO₃, mechanically introduced and oriented dislocation networks produced strongly anisotropic domain-wall pinning and electromechanical response, while excessive dislocation density suppressed domain mobility and reduced dielectric and piezoelectric properties [97]. Atomistic simulations further indicate that dislocation-induced heterogeneous stress redistributes polarization and modifies switching trajectories and hysteresis, with the dislocation density changing the balance between polarization stability and switching sharpness [98]. Dislocations should therefore not be classified as uniformly detrimental or beneficial; their functional role depends on whether their local fields stabilize reversible domain configurations or immobilize the switching pathways required by the component.

Microstructure sets the spatial limits of this process. In ceramics, grain size, grain-boundary chemistry, porosity, texture, secondary phases, and residual stress determine which domain configurations are accessible under field [99]. Grain boundaries may block wall motion, concentrate field, trap charge, or impose incompatible strain on neighboring grains. A high intrinsic piezoelectric response can be weakened by microstructural barriers, while a moderate intrinsic lattice response can become useful when domain mobility and grain-scale compatibility remain favorable [100].

Thin films introduce a different set of constraints. Substrate clamping, epitaxial strain, film thickness, texture, electrode roughness, and interfacial dead layers restrict wall configurations and switching pathways [101]. Ferroelastic domain switching may be suppressed by mechanical boundary conditions, while local strain gradients and depolarization fields can stabilize nonuniform domain structures. In ultrathin and nanoscale components, domain-wall motion competes with homogeneous-like switching, interfacial nucleation, and defect-assisted reversal, making the measured response highly sensitive to thickness and boundary conditions [102]. Texture may improve field alignment, but it can amplify anisotropic stress and local failure [103].

Local-probe measurements in non-hafnia thin films illustrate how mechanical constraint and domain reorientation can become direct carriers of functional response. Radio-frequency-sputtered K_{0.1}Na_{0.9}Nb_{0.97}Sb_{0.03}O₃ films exhibited nanoscale domain redirection and a local piezoelectric coefficient of approximately 73 pm/V, as measured by piezoresponse force microscopy [104]. BiMnO₃ films on Nb-doped SrTiO₃ showed a complementary pathway in which controlled local mechanical loading produced ferroelastic deformation and polarization redirection [105]. These examples extend the defect–domain–boundary framework to alkali-niobate and multiferroic-oxide films, where mechanical constraint and local domain accessibility can govern electromechanical functionality without fluorite-type switching.

A mature interpretation of ferroelectric functionality must place domain walls and microstructure between switching and transport. They are not separate microstructural annotations added after polarization has been measured. They define how the polar state moves, where charge accumulates, how strain is accommodated, and which regions degrade first [106].

6. Device-level consequences: memory, sensing, actuation, and reliability

The physics developed above becomes decisive when ferroelectric materials are integrated as components rather than measured as isolated polar solids [107]. A device does not use polarization as an abstract order parameter. It uses a field-written state, an interfacial boundary condition, a charge-transfer pathway, an electromechanical response, or a resistance contrast that must remain stable under electrical, thermal, mechanical, and time-dependent constraints. The relevant output is not the largest polarization, dielectric constant, strain, or memory window measured under ideal conditions, but the fraction of that response that survives defects, interfaces, leakage, trapping, domain-wall evolution, and repeated operation [108]. Table 1 compares representative quantitative benchmarks across distinct ferroelectric component classes. The values are presented with the decisive test condition and mechanistic constraint, since polarization, coercive field, memory window, resistance contrast, electromechanical response, and endurance depend on geometry and measurement protocol and are not directly interchangeable between architectures.

Table 1. Representative quantitative benchmarks across ferroelectric component classes.

Component/material	Test context	Switching metric	Functional/stability benchmark	Mechanistic interpretation and constraint
HZO capacitor with CeO _{2-x} interlayer [109]	6-nm HZO; accelerated retention at 358 K	HZO; $P_r = 21 \mu\text{C}/\text{cm}^2$; $E_c < 3 \text{ MV}/\text{cm}$	$< 5\%$ loss after 10^{11} cycles; projected retention > 10 years	Reversible oxygen accommodation suppresses imprint; epitaxial processing limits direct Si integration
Al _{0.64} Sc _{0.36} N [110]	capacitor 45-nm film; PUND at 10 kHz	$2P_r \approx 200 \mu\text{C}/\text{cm}^2$ under full reversal	10^8 full-switching cycles; $> 10^{10}$ partial-switching cycles	Partial switching lowers electrical stress; endurance values depend on reversal fraction
Flexible FeFET [111]	HZO/ITO 11.4-nm HZO; 100- μs program/erase pulses	Memory window = 2.78 V	$I_{\text{ON}}/I_{\text{OFF}} > 10^8$; $> 2 \times 10^7$ cycles; projected retention > 10 years	Polarization modulates the ultrathin ITO channel; trapping and pulse conditions affect the window
Bi _{1.8} Sm _{0.2} O ₃ /Nb:SrTiO ₃ FTJ [112]	1–4.6 nm barrier; read at -0.1 V	$P_r = 16.6 \mu\text{C}/\text{cm}^2$ at 1 nm	TER up to 1.2×10^9 ; $> 5 \times 10^9$ cycles; projected retention 10 years	Polarization modulates both ferroelectric and semiconductor depletion barriers
Domain-engineered Bi ₄ Ti ₃ O ₁₂ ceramic [113]	Bulk ceramic; low-field piezoelectric testing	$d_{33} = 38.5 \text{ pC}/\text{N}$	Stable response through 10^7 electrical cycles	Layered 180° walls support reversible response; low-field coefficients are not large-signal strain metrics

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Component/material	Test context	Switching metric	Functional/stability benchmark	Mechanistic interpretation and constraint
Mn-modified BiFeO ₃ –BaTiO ₃ harvester [114]	250 °C; 34-Hz resonant excitation	$d_{33} = 270$ pC/N; $T_d = 340$ °C	56.96 μ W/mm ³ ; stable after 10 ⁵ vibration cycles	Defect-dipole control improves insulation and domain stability; output depends on resonance and load
Freestanding membrane harvester [115]	PZT $\approx$ 250-nm membrane; repeated bending	$d_{33}^* \approx 585$ pm/V	$\approx$ 63.5 mW/cm ³ ; >60,000 bending cycles	Clamping release enhances domain mobility; power density depends on active-volume normalization
KNNS–Bi ₂ Te ₃ [116]	hybrid 50–50 wt.%; thermal characterization	Relaxor-like dielectric response	$ZT = 0.48$; $S = 1240$ μ V/K	Coupled pyroelectric–thermoelectric transport; component-level endurance remains unestablished

Note: Indium tin oxide (ITO); on/off current ratio (I_{ON}/I_{OFF}); piezoelectric coefficient (d_{33}); depolarization temperature (T_d); effective piezoelectric coefficient (d_{33}^*); K_{0.5}Na_{0.5}Nb_{0.97}Sb_{0.03}O₃ (KNNS); dimensionless thermoelectric figure of merit (ZT); Seebeck coefficient (S). Values are architecture- and protocol-specific and should not be interpreted as directly interchangeable material constants.

The comparison shows that a large functional metric does not independently establish a superior operating state. Polarization, device output, and stability must be interpreted together with the defect, interface, domain, transport, and boundary-condition mechanisms that control each architecture.

In ferroelectric capacitors and FeRAM-type elements, switching stability is governed by the same variables that define the P - E response: domain reversal, interfacial screening, defect redistribution, leakage current, and fatigue [117]. A high remanent polarization has limited device value if the written state decays through depolarization fields, trap relaxation, imprint, or progressive domain-wall pinning. Endurance is equally dependent on the evolution of defects and interfaces during cycling. A component that switches cleanly in the first cycles can degrade when oxygen vacancies accumulate, interfacial barriers change, injected charge becomes trapped, or local fields concentrate at weak regions of the stack [109]. The switching field and excitation timescale therefore define a kinetic–reliability trade-off: higher voltage can shorten polarization-reversal transients, whereas increased driving field or longer cycle period can reduce fatigue endurance through switching-induced charge injection and progressive domain-wall immobilization [118,119].

FeFETs impose a stricter separation between polarization and charge trapping. The memory window reflects the electrostatic modulation of the semiconductor channel, but also includes interface-state occupancy, oxide traps, charge injection, mobile ions, and depolarization-driven relaxation [111]. A threshold-voltage shift is not automatically a ferroelectric memory state. The useful state is the part of the shift retained after trap-assisted contributions, retention loss, imprint, and read-disturb effects are constrained. In this geometry, ferroelectric switching and semiconductor interface physics are not parallel problems; they define the same operating boundary [120]. Deliberate polarization–trapping coupling can enlarge the electrical memory window, but uncontrolled interfacial trapping may invert the hysteresis sense or destabilize the separation between states; a wider window therefore does not by itself constitute a larger polarization-controlled memory margin [121,122].

Ferroelectric tunnel junctions translate polarization reversal into barrier modulation. Their central functional quantity is not polarization alone but tunneling electroresistance arising from polarization-dependent barrier height, barrier width, interface dipoles, screening asymmetry, and local electronic structure [112]. Ultrathin dimensions make this response highly sensitive to defects, roughness, oxygen vacancies, dead layers, and localized conductive paths. A resistance contrast can arise from polarization-modulated tunneling, but also from trap-assisted tunneling, filamentary conduction, redox changes, or interface degradation. The device claim becomes strong only when resistance states track reversible polarization and remain stable under cycling without evolving into defect-dominated conduction [123].

Sensors and actuators rely on a different expression of the same coupled physics. Dielectric, piezoelectric, and electromechanical response depend on lattice contribution, domain-wall mobility, ferroelastic reconfiguration, defect pinning, leakage losses, mechanical boundary conditions, and field amplitude [113]. A large small-signal coefficient does not guarantee stable large-signal actuation. A strong strain response may carry excessive hysteresis, drift, aging, or fatigue if domain walls move irreversibly or defects redistribute during cycling. For sensors, charge noise, dielectric loss, leakage, pyroelectric drift, and aging may dominate sensitivity and stability [124]. For actuators, the relevant figure is not only the strain amplitude but also the reversible strain under repeated field and mechanical constraint.

In piezoelectric ceramics, the operating state is additionally constrained by phase coexistence, grain-boundary compatibility, defect-dipole alignment, insulation resistance, depolarization temperature, and mechanically induced microdamage. These variables determine whether a large piezoelectric coefficient remains usable under temperature, cyclic field, and mechanical loading. In lead-free ceramics designed for high-temperature energy harvesting, rational dopant modulation has been used to control defect chemistry while preserving insulation resistance and polarization stability, enabling operation at temperatures up to 250 °C [114]. Bipolar-fatigue studies in BaZrO₃-modified (K,Na)NbO₃ further show that phase coexistence and domain-wall depinning can improve cyclic stability, whereas accumulated microstructural damage can suppress the electromechanical response even when the initial piezoelectric performance is high [125]. Ceramic sensors and actuators must therefore be evaluated through the coupled evolution of polarization, domain mobility, electrical insulation, and structural integrity rather than through d_{33} or strain amplitude alone.

Energy-harvesting and flexible ferroelectric components further expose the role of interfaces and fatigue. Mechanical bending, substrate compliance, polymer/ceramic interfaces, electrode adhesion, local strain gradients, and repeated deformation alter domain configurations and charge extraction [126]. In flexible stacks, the active ferroelectric layer may remain polar while the component fails through interfacial delamination, electrode cracking, leakage growth, or unstable mechanical boundary conditions. The limiting variable is often not intrinsic piezoelectricity but the stability of polarization-driven charge generation across a deformable, defect-sensitive, and interface-rich architecture [127].

Recent flexible architectures also demonstrate that releasing mechanical constraint can alter the polar state itself rather than merely improve bendability. Freestanding (111)-oriented PZT membranes obtained by removing substrate clamping exhibited a transition toward a lower-symmetry polarization configuration, enhanced domain-wall mobility, faster switching, an effective piezoelectric coefficient of approximately 585 pm/V, and stable operation beyond 60,000 bending cycles [115]. Lead-free hybrid architectures provide a complementary route: vertically aligned BiFeO₃–BaTiO₃ micropillars supported by poly(vinylidene fluoride-co-trifluoroethylene) [P(VDF-TrFE)] redistribute strain within the active layer and combine mechanical compliance with polarization-driven sensing and energy

harvesting [128]. These systems show that flexible-component performance depends on the preservation of polarization, strain transfer, electrode continuity, interfacial adhesion, and cyclic mechanical stability across the complete architecture.

Hybrid energy-conversion components extend the operating-state framework beyond systems in which polarization is the only functional carrier. A KNNS–Bi₂Te₃ nanocomposite combined pyroelectric and thermoelectric response, reaching a pyroelectric figure of merit $F_{v,sink} = 9.05 \times 10^5$ V/W, $ZT = 0.48$, and a Seebeck coefficient of approximately 1240 μ V/K for the composition containing 50 wt.% KNNS and 50 wt.% Bi₂Te₃ [116]. The Bi₂Te₃ fraction also introduced relaxor-like behavior into the KNNS-based system. In such architectures, functional output is governed by the coupled evolution of polar order, thermal excitation, dielectric relaxation, interfaces, and carrier transport rather than by polarization magnitude alone.

The main functional outputs of ferroelectric components may arise from more than one physical carrier, and the most common mechanistic ambiguities are summarized in Table 2.

Table 2. Mechanistic ambiguities in advanced ferroelectric component response.

Measured response	Possible physical carriers	Required separation	Risk if unresolved
Remanent polarization	Reversible switching; leakage-integrated charge; trapped charge; ionic redistribution	Switching-current analysis; leakage correction; pulse protocols; retention after field removal	Remanent charge may be assigned to switching without excluding conductive or trapped-charge contributions
Coercive field shift	Wall pinning; internal bias; asymmetric injection; interface traps; vacancy migration	Bias-history tests; stack comparison; cycling and frequency dependence	Imprint or trap charging may be misread as intrinsic switching asymmetry
Memory window	Polarization modulation; interface trapping; oxide traps; mobile ions; semiconductor depletion	Retention, endurance, temperature dependence, C - V response, and trap-sensitive protocols	Threshold-voltage shift may be overassigned to ferroelectric polarization
Resistance contrast	Barrier modulation; trap-assisted tunneling; filamentary paths; redox changes; defect migration	Polarity-dependent tests; area scaling; cycling stability; transport-mechanism analysis	TER-like behavior may arise from defect-assisted or electrochemical conduction
Open or slanted P - E loop	Incomplete switching; dielectric loss; leakage; Maxwell–Wagner polarization; charge injection	Frequency dependence; current transients; PUND or pulse-based measurements	Loop shape may be treated as proof of ferroelectricity despite non-ferroelectric contributions
Wake-up behavior	Defect redistribution; domain depinning; phase stabilization; reduced internal bias; interface-charge rearrangement	Cycle-resolved switching, leakage, structural, and spectroscopic tracking	Initial improvement may be interpreted as intrinsic activation without resolving defect evolution
Fatigue	Wall immobilization; charge trapping; defect clustering; interface degradation; leakage acceleration	Endurance tests with leakage, imprint, and switching-current separation	Loss of response may be assigned to polarization degradation alone

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Measured response	Possible physical carriers	Required separation	Risk if unresolved
Conductive domain-wall signal	Charged-wall conduction; surface leakage; grain-boundary paths; electrode effects; defect-rich channels	Local-probe correlation with domain structure; polarity reversal; contact and environmental controls	Local current may be assigned to walls without excluding extrinsic conduction paths

Note: Capacitance-voltage (C - V).

6.1. Unified defect–interface evolution in wake-up, fatigue, and imprint

Wake-up, fatigue, and imprint are distinct electrical manifestations of an evolving defect–interface–domain state. Wake-up denotes a cycle-induced increase in switchable polarization or progressive opening of the hysteresis loop; fatigue denotes the loss of switchable polarization, strain, or functional state contrast under repeated operation; imprint denotes a directional internal bias expressed through horizontal loop displacement, unequal positive and negative coercive fields, or asymmetric retention. These phenomena share mobile defects, trapped charge, interfacial screening, domain-wall accessibility, phase stability, and residual stress as state variables, but differ in the direction, symmetry, and reversibility of their electrical evolution. A wake-up-like increase in remanence can therefore originate from depinning of charged walls or from the conversion of a minor loop into a major loop as the internal bias and domain-nucleation state evolve, rather than from an increase in intrinsic polarization [129,130].

Fatigue begins when cycling drives the operating state away from reversible domain reconfiguration. Charge injection at a defective electrode/ferroelectric interface can generate local depolarization fields and suppress domain reversal, whereas defect accumulation at charged ferroelastic walls can increase internal stress and immobilize otherwise switchable regions [131,132]. The resulting degradation may be irreversible within the operating window or partially recoverable after rest, thermal treatment, prolonged poling, or a modified field protocol, depending on whether the limiting state is governed by interfacial charge, defect–wall association, local structural conversion, or permanent chemical damage. Wake-up and fatigue are therefore not universal consecutive stages; their crossover depends on field amplitude, pulse duration, cumulative cycle count, temperature, and the relaxation interval between cycles.

Imprint is the symmetry-breaking branch of the same state evolution. Asymmetric screening, aligned defect dipoles, trapped carriers, interfacial redox states, or strain gradients establish a persistent built-in field that shifts the effective switching threshold for each polarity. This field can redistribute cycling stress asymmetrically and thereby modify both the apparent wake-up trajectory and the onset of fatigue. Spatially resolved measurements in BiFeO₃ have correlated imprint with charged defects distributed through the bulk and interfaces, showing that loop displacement can encode a frozen-in defect configuration rather than a change in spontaneous polarization [133]. Distinguishing wake-up, fatigue, and imprint therefore requires cycle-resolved switched charge, positive and negative coercive fields, loop offset, leakage, retention, and recovery measurements, correlated where possible with structural or local-domain analysis.

7. Evidence hierarchy and reporting criteria for ferroelectric component claims

Advanced ferroelectric component claims must be proportional to the physical state that has actually been resolved. A polar phase, a switchable ferroelectric, an interface-controlled memory window, a trapped-charge response, a conductive domain-wall contribution, and a reliable component are not interchangeable evidentiary states. Each one constrains a different part of the operating system: lattice polarity, field-driven reversal, electrostatic boundary conditions, carrier trapping, local transport, or degradation under repeated operation [134].

The central difficulty is that component-level response is usually mixed. Electrodes impose finite screening, semiconductor contacts introduce traps and band bending, thin films accumulate built-in fields, mobile defects reshape local bias, leakage currents distort hysteresis, and domain walls add extrinsic nonlinearity [135]. Under these conditions, reproducible function alone does not identify the physical carrier of the response. The evidentiary hierarchy must separate reversible polarization from charge injection, trapped charge, leakage, ionic migration, domain-wall motion, and fatigue-related degradation [136]. Table 3 condenses these distinctions into evidence stages, architecture-dependent diagnostic gates, and maximum defensible claims.

Table 3. Evidence hierarchy and diagnostic gates for ferroelectric component claims.

Evidence stage or diagnostic gate	Minimum correlated evidence and key exclusion	Maximum defensible claim
1. Polar identity [137,138]	Polar symmetry or direct polar displacements confirmed by correlated independent probes; exclude electrostatic, flexoelectric, ionic, topographic, or nonpolar non-centrosymmetric contrast.	Polar state supported; switchability not established.
2. Reversible switchability [139,140]	Polarity-reversed switching current with remanent write-read/PUND response or off-field domain reversal; exclude leakage, displacement current, transient charging, and ionic hysteresis.	Reversibly switchable ferroelectric state under the stated protocol.
3. Interface control [141]	Controlled electrode, interlayer, or screening variation at comparable phase, thickness, and processing; exclude bulk-structure, stress, defect-density, and trapping changes.	Interface-modulated response; interface-controlled only when causality is resolved.
4. Trapped- and mobile-charge separation [70,71]	Compare switched charge, P_r , threshold or resistance shift, retention/recovery, and bias- or temperature-history dependence; constrain trapping, ionic redistribution, leakage, and backswitching.	Polarization-, trapping-, ionic-, or coupled-state response.
5. Leakage and circuit effects [76,142]	J - E / J - T analysis with geometry and frequency scaling; physically plausible parameters; $V_{FE}(t)$, RC, rise-time, and series-resistance checks.	Transport regime consistent with stack physics; switching separated within the tested range.
6. Domain-wall contribution [92,143]	Verified subcoercive Rayleigh or harmonic response and/or co-registered PFM/c-AFM with contact, topographic, polarity, surface, and environmental controls.	Quantified wall contribution and/or locally resolved wall conduction.

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Evidence stage or diagnostic gate	Minimum correlated evidence and key exclusion	Maximum defensible claim
7. Functionality and reliability [144]	Architecture-specific retention, endurance, imprint, drift, and variability with replicate count, failure criterion, and realistic electrical, thermal, or mechanical stress window.	Device-relevant functionality and reliability within the tested window.

Note: Current density-electric field (J - E); current density-temperature (J - T); piezoresponse force microscopy (PFM); conductive atomic force microscopy (c-AFM). Rows 3–6 are architecture-dependent diagnostic gates, not mandatory sequential stages. Claims remain limited to the complete evidence package and operating window demonstrated.

7.1. Ferroelectric identity and switchability

Ferroelectric identity begins with structural and symmetry evidence, but it cannot end there. Phase assignment, non-centrosymmetric symmetry, polar distortion, Raman-active local symmetry breaking, second-harmonic generation, electron diffraction, or nanoscale polar contrast support a polar-material claim, not necessarily a switchable-ferroelectric claim [138]. Reversible polarization requires constrained evidence of field-driven reorientation, ideally through consistent macroscopic P - E response, switching-current signatures, pulse-based protocols, local PFM switching, domain reversal, or field-dependent electromechanical response [140]. The critical issue is the separation of polarization reversal from leakage, dielectric loss, charge injection, ionic migration, electrochemical drift, and trapped-charge contrast [139]. Coercive field, remanent polarization, loop shape, and local hysteresis are meaningful only after this separation has been made. In capacitors, semiconductor-coupled stacks, tunnel junctions, sensors, and actuators, the same electrical response may contain switching, trapping, injection, relaxation, or conductive contributions. A defensible claim scales with the evidence: structural polarity supports polar identity, artifact-constrained reversal supports switchability, and component-level ferroelectric functionality requires a further link between switching, boundary conditions, leakage, trapped charge, and retention of the written state.

7.2. Interface-controlled switching and trapped-charge effects

Interface-controlled switching claims require evidence that the boundary condition modifies polarization reversal, retention, or the apparent memory state. Work-function mismatch, finite screening length, dead layers, Schottky barriers, semiconductor depletion, interface traps, and built-in fields can all shift coercive voltage, stabilize internal bias, broaden switching distributions, or generate imprint. In ferroelectric-semiconductor components, a memory window may arise from polarization, trapped charge, mobile ions, or a combination of these contributions [145]. Threshold-voltage shifts, resistance changes, or asymmetric hysteresis cannot be assigned to ferroelectric switching without separating trap charging and detrapping from remanent polarization. Stronger assignments require bias-history analysis, pulse protocols, retention after write/erase states, temperature or frequency dependence, interface-sensitive spectroscopy, capacitance-voltage response, or comparison between symmetric and asymmetric stacks [146]. The physical claim becomes credible when the interface is not treated as a passive contact but as an electrostatic boundary that governs screening, charge injection, band bending, and the stability of the polar state under operation.

7.3. Leakage, conduction mechanism, and nonideal electrical response

Leakage is not a secondary correction in ferroelectric components; it can define the measured electrical response. Current-density analysis, field dependence, temperature dependence, pulse-width effects, and cycling behavior are needed to distinguish switching current from injection-limited conduction, Schottky emission, Poole–Frenkel transport, trap-assisted tunneling, space-charge-limited conduction, ionic migration, or electrochemical drift [142]. Apparent rate-dependent shifts in coercive field or switching-current maxima must also be tested against the circuit time constant and instrumental rise time. An intrinsic kinetic assignment requires direct measurement or reconstruction of $V_{FE}(t)$, together with scaling against series or load resistance, excitation frequency, and electrode area. Lossy P - E loops, open hysteresis, remanent-like charge, and frequency-dependent polarization can all arise from non-ferroelectric pathways when conductive or interfacial contributions dominate. A credible conduction assignment must remain consistent with the device geometry, electrode material, barrier profile, defect chemistry, and operating field. Leakage should therefore be treated as an active physical variable: it may degrade retention, accelerate fatigue, distort coercive fields, generate false ferroelectric-like loops, or provide a parasitic transport channel that competes with polarization-controlled functionality [135].

7.4. Domain-wall and microstructural contribution

Domain-wall and microstructural claims require evidence that the functional response is shaped by mobile, pinned, conductive, or strain-coupled domain structures rather than by average polarization alone. Domain-wall mobility can enhance dielectric, piezoelectric, and electromechanical response, while defect pinning, grain-boundary constraints, film texture, local strain gradients, and charged-wall compensation can increase losses, hysteresis, aging, or field-dependent instability. Rayleigh analysis of field-amplitude-dependent permittivity or piezoelectric response provides a quantitative estimate of field-independent and irreversible contributions only when a subcoercive Rayleigh range has been experimentally verified [147]. Conductive domain walls must be separated from leakage through surrounding grains, surface conduction, electrode effects, and defect-rich paths [143]. Such an assignment requires spatially co-registered PFM and c-AFM measurements of the same region, together with topographic, contact, bias-polarity, surface, and environmental controls. In ceramics, the grain boundary network may limit switching and transport even when domains remain locally active. In films, substrate strain, texture, thickness, and electrode boundary conditions can define which wall configurations are accessible under the field. A domain-wall contribution becomes defensible when structural, electromechanical, electrical, or local-probe evidence connects wall state with switching kinetics, nonlinearity, dissipation, transport, or reliability [148].

7.5. Device-relevant functionality and reliability-level claims

Device-relevant claims require more than high polarization, large piezoelectric response, strong dielectric tunability, resistance contrast, or a wide memory window. The response must remain stable under conditions that resemble operation: repeated cycling, finite temperature, realistic voltage window, retention delay, mechanical boundary conditions, environmental exposure, and device-to-device variability [144]. FeRAM and FeCAP claims require endurance, fatigue, imprint, retention, leakage,

and switching-current consistency. FeFET claims require separation between polarization-induced threshold-voltage shift and trap-mediated memory. FTJ claims require barrier modulation linked to polarization rather than filamentary or defect-assisted conduction [149]. Sensor, actuator, energy-harvesting, and flexible-component claims require drift, hysteresis, fatigue, noise, strain stability, and electromechanical reversibility. A component-level claim becomes physically meaningful only when the functional output and its degradation pathway are interpreted within the same operating-state framework [144].

8. Conclusions

Polarization is the necessary order parameter of a ferroelectric component, but not its complete operating state. In advanced electronic components, functional response is carried by a coupled configuration of switchable polarization, defect distributions, interfacial screening, trapped charge, leakage pathways, domain-wall mobility, and field-dependent kinetics. Polarization magnitude, crystal phase, and nominal composition remain essential descriptors, yet they become insufficient once the component operates under repeated electrical, thermal, mechanical, or interfacial constraints.

The stability of this operating state defines reliability. Wake-up, fatigue, imprint, retention loss, leakage growth, threshold-voltage drift, resistance-state instability, and electromechanical degradation are not isolated failure labels. They are time-dependent expressions of how defects migrate, traps fill and empty, interfaces screen or inject charge, domain walls pin or depin, and local fields redistribute under operation. A ferroelectric component fails when the coupled switching-interface-transport state can no longer preserve the functional contrast it was designed to store, sense, actuate, or convert.

This perspective changes the meaning of performance. A large remanent polarization, a wide memory window, strong tunneling electroresistance, high dielectric tunability, or large electromechanical strain is not sufficient by itself. The relevant question is whether the response remains physically traceable to reversible switching, stable boundary conditions, controlled charge transport, and bounded degradation across the field, timescale, and measurement protocol under which it is extracted. Device-level functionality begins where material properties survive the electrical and microstructural conditions imposed by the component architecture.

A hierarchy of evidence is therefore essential for this field. Polar identity, switchable ferroelectricity, interface-controlled switching, trapped-charge response, leakage-limited behavior, domain-wall contribution, and reliability-level functionality support different claims. Treating them as equivalent weakens comparison across materials and devices. The strongest studies will be those that connect the measured output to the state that carries it, separating polarization reversal from charge injection, trapped charge, conductive hysteresis, interfacial drift, and microstructural degradation.

Advanced ferroelectric components will become more predictable, comparable, and durable when switching, defects, interfaces, charge transport, and reliability are treated as one coupled materials-physics problem rather than as separate descriptors of performance.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

J. E. Leal-Perez: Conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review and editing; C. Vargas-Arana: conceptualization, methodology, formal analysis; J. Flores-Valenzuela: conceptualization; J. C. Leal-Zayas: formal analysis, investigation; and R. A. Vargas-Ortiz: conceptualization.

Conflict of interest

The authors declare no conflict of interest.

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