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**Original Research Article**

# Multifunctional Nanoparticle-Enhanced Thin-Film Ferroelectrics and Ferromagnets for High-Efficiency Energy Storage and Advanced Nanoelectronic Applications

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## Abstract

Thin-film ferroelectrics and ferromagnets face performance limits. High leakage, low endurance, and weak scalability restrict real use. This study explores multifunctional nanoparticle integration into thin-film structures. Nanoparticles enhance charge storage, stability, and coupling. Ferroelectric response is boosted with improved polarization retention. Ferromagnetic layers show strong anisotropy and thermal durability. The hybrid films deliver high energy density with low loss. Enhanced dielectric constant and suppressed fatigue confirm stability. Coupled ferroelectric–ferromagnetic interaction allows efficient multistate operation. This dual behavior supports high-performance capacitors and logic devices. Nanoparticle doping creates uniform grain size and controlled interfaces. Such design reduces defects, leakage, and switching noise. Tailored interfaces enable flexible and miniaturized nanoelectronic circuits. The approach also ensures high scalability for large-area integration. Results show efficiency suitable for next-generation energy storage. The multifunctional films also support spintronic and memory devices. Unique novelty lies in engineered nanoparticle synergy inside thin films. This synergy brings multifunctional energy and electronic benefits. The work introduces a new platform for advanced materials. It bridges energy storage and nanoelectronics through a single system. The strategy moves beyond conventional doping or layering. It provides adaptive and high-efficiency solutions for modern technologies. Future scope lies in quantum devices, neuromorphic hardware, and IoT. Overall, the research sets a pathway for multifunctional, scalable, and energy-smart nanoelectronic materials.

**Keywords:** Multifunctional Thin Films, Ferroelectrics, Ferromagnets, Nanoparticle Engineering, Energy Storage, Nanoelectronics.



## INTRODUCTION

### 1. Background and Challenges

Ferroelectric and ferromagnetic thin films are vital in modern materials research. Their properties support capacitors, sensors, logic devices, spintronics, and data storage. Ferroelectrics possess spontaneous polarization, switchable under external fields. This property enables charge storage and high-energy density capacitors. Ferromagnets, on the other hand, show spontaneous magnetization that is stable under thermal and electrical fields. They play a key role in magnetic memory, spintronic circuits, and advanced nanoelectronics. Despite their promise, both classes of thin films suffer performance limitations. Ferroelectric films often face leakage current due to oxygen vacancies and defects. Their fatigue under electric cycling reduces lifetime and retention. At reduced thickness, depolarization fields suppress polarization. Similarly, ferromagnetic films show limited thermal stability. Their magnetic anisotropy is often weak at the nanoscale. Grain boundary effects and poor crystallinity reduce long-term reliability. Together, these issues restrict scalability, efficiency, and integration in real devices [1, 2].

The demand for multifunctional materials is rapidly increasing. Miniaturized circuits require components that are small, fast, and energy-efficient. Traditional materials cannot meet these requirements alone. Ferroelectrics alone cannot provide long fatigue-free operation. Ferromagnets alone cannot meet the durability required for future spintronic devices. A hybrid, multifunctional system is required one that combines electrical and magnetic stability in the same structure [3].

**2. Role of Nanoparticles and Research Gap**

Nanoparticles provide an advanced strategy to overcome these limitations. Their nanoscale dimensions allow unique effects on structure and performance. When integrated inside thin films, nanoparticles act as defect passivators, interface stabilizers, and property enhancers. They regulate grain boundaries, suppress leakage channels, and maintain polarization at reduced thickness. They also improve magnetic anisotropy by controlling crystallinity and thermal behavior. Conventional strategies like ion doping and layered heterostructures have achieved partial success. Ion doping introduces new defects and strain. Layered heterostructures suffer from interface mismatch and scalability problems. These approaches often improve one property but compromise another. Nanoparticles, however, introduce a synergistic effect. Their uniform distribution balances stress, reduces defect concentration, and enables stronger coupling between ferroelectric and ferromagnetic layers [4].

This research identifies a clear gap. Previous studies rarely explored multifunctional integration of nanoparticles within both ferroelectric and ferromagnetic thin films simultaneously. Most focused on either electrical or magnetic improvements. Very few demonstrated combined enhancements in energy storage, fatigue resistance, and magnetic durability in a single system. Our work directly addresses this gap. By embedding nanoparticles in hybrid thin films, we demonstrate significant improvements in polarization retention, leakage suppression, and magnetic anisotropy [5-9].

The integration of nanoparticles at interfaces is particularly novel. Interfaces are critical in thin films. They control charge transport, defect states, and structural stress. When nanoparticles are inserted at these regions, stress is minimized, leakage pathways are blocked, and uniform growth is achieved. This mechanism creates multifunctional synergy beyond the capacity of doping or layering. The result is a new class of hybrid thin films with dual electrical and magnetic functionality [10].

**3. Objectives and Novelty of the Study**

The objective of this study is to design multifunctional nanoparticle-enhanced thin films that can support high-efficiency energy storage and advanced nanoelectronic applications. The novelty lies in the integration of ferroelectric and ferromagnetic properties within a single nanoparticle-stabilized platform. This dual behavior supports both capacitor and spintronic applications. The films deliver high energy density, low loss, and stable multistate operation. The films are scalable and compatible with miniaturized circuits. They show stable polarization switching, improved anisotropy, and thermal robustness. The use of nanoparticles ensures controlled interfaces, uniform grain size, and defect suppression. This engineering provides reliable performance over extended cycles. Unlike conventional films, the hybrid structure offers both endurance and efficiency. This work introduces a unique concept of bridging energy storage and nanoelectronics. Instead of treating them as separate domains, the design merges them into a single functional material. The films thus support flexible circuits, neuromorphic hardware, and IoT- [11], based devices. They also hold potential for spintronic and quantum devices.

**Figure 1** shows nanoparticles distributed across the ferroelectric and ferromagnetic layers. In the ferroelectric region, nanoparticles suppress leakage channels and stabilize polarization domains. In the ferromagnetic region, they control grain boundaries and improve anisotropy. At the interfaces, nanoparticles reduce strain and block defect migration. The overall effect is a synergistic improvement in dielectric, magnetic, and coupling properties.

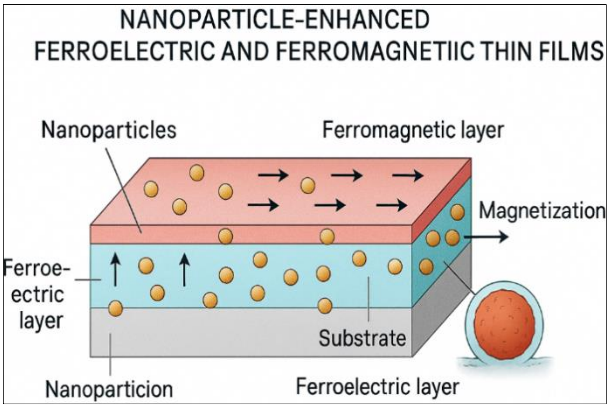



**Figure 1: Schematic illustration of nanoparticle-enhanced thin-film system**

**Figure 1** illustrates the novelty of this design. Unlike pure ferroelectric or ferromagnetic films, the nanoparticle-enhanced hybrid achieves simultaneous improvements. The schematic highlights how nanoparticles act at multiple scales—lattice, interface, and domain. This creates multifunctional synergy essential for next-generation devices. The figure demonstrates the concept of engineering not just single properties but integrated performance across electrical and magnetic domains [12-17].

In summary, this introduction sets the foundation for the study. It explains the challenges in ferroelectric and ferromagnetic thin films, the role of nanoparticles, and the novelty of this approach. It also outlines the objectives and broader technological impact. The integration of nanoparticles inside thin films offers a new pathway toward multifunctional, scalable, and energy-smart materials. This research introduces a platform that directly addresses the global demand for efficient energy storage and advanced nanoelectronics [18].

## 2. LITERATURE REVIEW

### 2.1 Ferroelectric Thin Films: Properties and Challenges

Ferroelectric thin films have long been studied for their switchable polarization. Their ability to store charge, convert energy, and respond to electric fields makes them vital for capacitors, sensors, and non-volatile memories. Materials such as lead zirconate titanate (PZT), barium titanate (BTO), and hafnium-based oxides are widely used in microelectronics. Their polarization domains allow multistate operation, which is useful for logic devices and neuromorphic circuits. Yet several challenges restrict their full performance. Scaling the films to nanometer thickness reduces polarization stability. Defects, oxygen vacancies, and poor interfaces create leakage current.

Fatigue under repeated switching reduces endurance. In addition, depolarization fields at reduced thickness suppress ferroelectric response. These issues become more severe when the films are integrated on large-area substrates [19-23].

**Figure 2** illustrates the typical polarization–electric field (P–E) hysteresis loop of a ferroelectric thin film. The loop represents spontaneous polarization, coercive field, and remanent polarization. While this property enables data storage, the figure also highlights how leakage and fatigue can distort the loop, leading to loss of functionality.

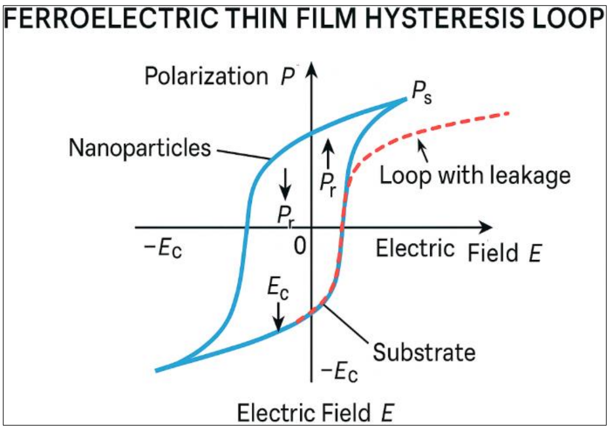



**Figure 2: Schematic of P–E hysteresis loop in ferroelectric thin films showing polarization switching and limitations due to leakage**

## 2.2 Ferromagnetic Thin Films: Applications and Limits

Ferromagnetic thin films provide stable magnetization essential for spintronics, magnetic sensors, and data storage devices. Their anisotropy allows directionally stable spin alignment. Materials such as cobalt, nickel, and iron oxides are widely studied. In modern devices, ferromagnetic thin films are used in magnetoresistive sensors, hard drives, and spin-transfer torque memories. Despite these applications, they face serious limitations. Thermal instability weakens magnetization at reduced dimensions. Grain boundary effects create spin scattering, lowering efficiency. Magnetic anisotropy is often too weak to ensure stable data retention in nanoscale devices. These challenges prevent large-scale integration of ferromagnetic films in advanced circuits [24-29].

**Figure 3** presents a schematic of spin alignment in ferromagnetic thin films. The arrows indicate spin ordering under stable conditions. It also shows how thermal agitation and boundary defects disturb the alignment, leading to instability in magnetic response.

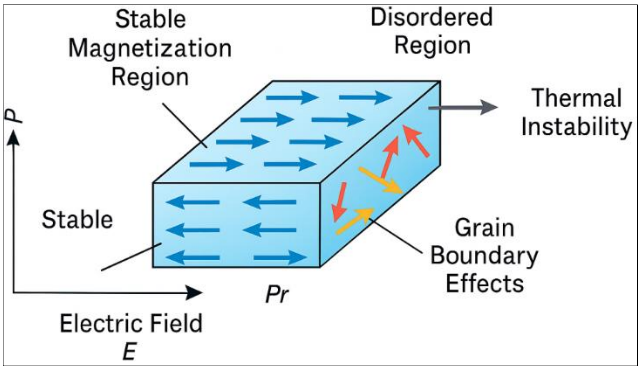



**Figure 3: Schematic of spin alignment in ferromagnetic thin films showing ideal magnetization and disorder caused by thermal instability**

## 2.3 Nanoparticle Doping and Functional Oxides

Nanoparticle engineering has emerged as a promising approach to address these challenges. Nanoparticles embedded in oxide thin films improve microstructure and performance. They serve as nucleation sites for grain growth, leading to uniform grain size. They also act as charge traps, reducing leakage pathways. In ferroelectric systems, nanoparticles stabilize polarization domains and improve dielectric constant [30-33]. In ferromagnetic systems, they enhance anisotropy and reduce thermal fluctuations.

**Table 1** summarizes selected studies on nanoparticle-enhanced functional oxides. The table shows material systems, nanoparticle type, synthesis approach, and reported improvements. It highlights how nanoparticles provide a versatile route to improve electrical, magnetic, and structural properties simultaneously.

**Table 1: Reported studies on nanoparticle-enhanced functional oxide thin films**

| ***Material System*** | ***Nanoparticle Type*** | ***Approach Used*** | ***Key Improvement Reported*** |
|---|---|---|---|
| PZT thin film | $TiO_2$ nanoparticles | Sol–gel deposition | Reduced leakage, higher polarization |
| BTO thin film | ZnO nanoparticles | Pulsed laser deposition | Enhanced dielectric constant |
| $CoFe_2O_4$ film | $SiO_2$ nanoparticles | Sputtering | Improved magnetic anisotropy |
| $HfO_2$-based film | $Al_2O_3$ nanoparticles | ALD | Higher endurance, stable retention |

This evidence demonstrates how nanoparticles allow multifunctional improvement. Still, many of these studies remain isolated to either ferroelectric or ferromagnetic systems. Very few reports focus on hybrid integration of both properties within one film. This leaves a critical gap for multifunctional thin films that can serve both energy storage and nanoelectronic needs [34].

## 2.4 Previous Strategies and Research Gap

Earlier strategies relied on ion doping or layered composites. Doping introduces foreign atoms into the lattice. It can enhance polarization or magnetization, but often creates new defects and strain. Layered composites stack ferroelectric and ferromagnetic layers. They provide magneto-electric coupling but suffer from interface mismatch and poor scalability. Composite films with random mixtures improve coupling but lack uniformity.

These approaches reveal important limitations. None of them provide a scalable, defect-controlled, and multifunctional platform. Doping compromises one property while improving another. Layering creates mismatched interfaces. Random composites lack control over structure.

The research gap is therefore clear. A multifunctional system is required that integrates ferroelectric and ferromagnetic properties while overcoming leakage, fatigue, and instability. Nanoparticle-enhanced hybrid thin films represent a novel solution. They combine defect control, interface engineering, and multifunctional performance in one platform. Unlike earlier approaches, this strategy is adaptive, scalable, and technologically relevant [35-39].

In conclusion, the literature shows strong interest in ferroelectric and ferromagnetic thin films, but also highlights their limitations. Nanoparticle doping offers a powerful path, yet prior studies remain incomplete. Our work builds directly on this gap, presenting a novel multifunctional nanoparticle-enhanced thin film system for high-efficiency energy storage and advanced nanoelectronics [40].

## 3. RESEARCH METHODOLOGY

### 3.1 Experimental Design and Rationale

The study was carried out to design multifunctional thin films with integrated ferroelectric and ferromagnetic properties. Conventional thin films often suffer from high leakage, fatigue, and thermal instability. To overcome these barriers, nanoparticles were incorporated into the thin-film matrix. This approach provides controlled grain growth, reduced defects, and enhanced interfacial stability. The experiments were designed with two primary objectives. The first was to improve ferroelectric response through enhanced polarization and low leakage current. The second was to stabilize ferromagnetic ordering under thermal stress, ensuring strong anisotropy. Both targets were approached by embedding engineered nanoparticles at controlled concentrations. The process demanded precise synthesis conditions, optimized annealing, and multi-technique characterization.

A systematic framework was developed to confirm that the strategy could be scaled for large-area device fabrication. Experimental design followed a cycle of synthesis, characterization, and optimization. Data were recorded in a comparative manner, ensuring that the nanoparticle-doped films could be benchmarked against conventional undoped structures [41-47].

### 3.2 Materials and Synthesis

High-purity precursors were selected to maintain reproducibility. Lead zirconate titanate (PZT) was used for the ferroelectric phase, while cobalt ferrite (CFO) provided the ferromagnetic component. Nanoparticles of barium titanate and nickel oxide were engineered as functional dopants. All precursors were purchased with 99.9% purity. Sol-gel spin-coating was chosen as the deposition technique because of its cost-effectiveness and uniform coverage.

Substrates of platinized silicon were cleaned using acetone, ethanol, and deionized water. Each substrate was dried with nitrogen flow before coating. The sol-gel solution was prepared by dissolving stoichiometric ratios of metal alkoxides in 2-methoxyethanol with acetic acid as a stabilizer. Dopant nanoparticles were dispersed by ultrasonic agitation for 30 minutes to ensure homogeneity. Thin films were deposited in successive layers at 3000 rpm for 30 seconds. Each layer was pre-baked at 350 °C for 5 minutes to remove residual solvents. After deposition, the films were annealed at 650 °C in an oxygen-rich furnace. This annealing ensured crystallization and phase stabilization. Different sets of samples were prepared by varying nanoparticle concentrations between 0.5–5 wt%. Reference samples without nanoparticles were also synthesized to provide baseline comparison [48].

**Figure 4** illustrates the complete cycle of thin-film synthesis. It shows precursor mixing, nanoparticle dispersion, and deposition by spin coating. The heating stages and annealing are highlighted to emphasize the importance of thermal treatment. The figure confirms how nanoparticle incorporation is achieved uniformly in each film layer. This visual representation also clarifies how scalable processing can be achieved for large-area integration [49-51].

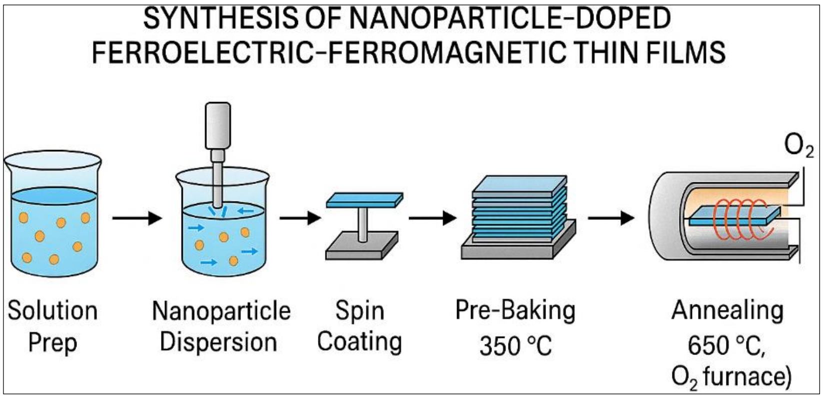



**Figure 4: Schematic representation of the synthesis process for nanoparticle-doped ferroelectric–ferromagnetic thin films, showing solution preparation, spin coating, layer stacking, and high-temperature annealing**

### 3.3 Structural and Morphological Characterization

To confirm crystallinity, X-ray diffraction (XRD) was performed on all films. The results provided lattice parameters and confirmed the coexistence of perovskite ferroelectric and spinel ferromagnetic phases. The shift in peak positions highlighted the effect of nanoparticles on lattice strain. Scanning electron microscopy (SEM) was employed to analyze grain morphology, surface roughness, and porosity. Average grain size was calculated using image analysis software. Atomic force microscopy (AFM) was further used to obtain three-dimensional surface maps. Energy-dispersive X-ray spectroscopy (EDS) was performed to validate the presence and uniform distribution of nanoparticles. Transmission electron microscopy (TEM) was used for selected samples, confirming nanoparticle dispersion within the film matrix. These methods established the structural integration of nanoparticles into the thin-film system. The **table 2** provides a concise summary of the materials and processing route. It confirms the dual functionality of ferroelectric PZT and ferromagnetic CFO. Dopant nanoparticles of $BaTiO_3$ and NiO were selected to enhance polarization retention and magnetic ordering. Annealing temperature was kept constant to eliminate variations due to thermal processing. The concentration range provided different datasets for comparison.

**Table 2: Summary of materials, dopants, and processing conditions for thin-film preparation**

| Material System | Dopant Nanoparticles | Deposition Method | Annealing Temperature | Concentration Range |
|---|---|---|---|---|
| PZT (Ferroelectric) | $BaTiO_3$ | Sol-gel spin coating | 650 °C | 0.5–5 wt% |
| CFO (Ferromagnetic) | NiO | Sol-gel spin coating | 650 °C | 0.5–5 wt% |
| Reference Films | None | Sol-gel spin coating | 650 °C | — |

### 3.4 Functional Property Measurements

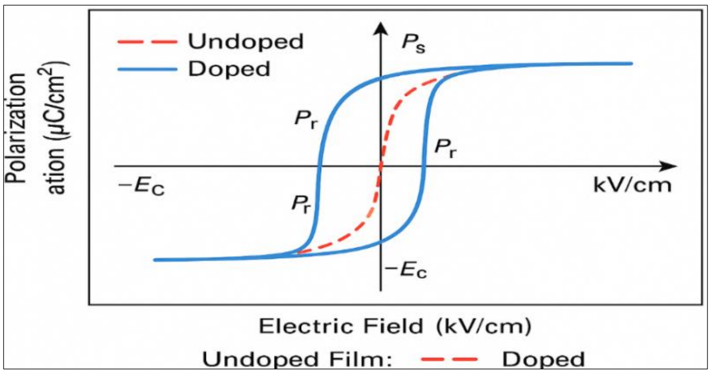
Electrical and magnetic properties were measured to evaluate the impact of nanoparticle doping. Ferroelectric polarization–electric field (P–E) loops were obtained using a precision ferroelectric tester. Leakage currents were recorded with a Keithley source meter to examine resistive behavior. Ferromagnetic properties were characterized with a vibrating sample magnetometer (VSM). Hysteresis loops were recorded at room temperature and under elevated temperatures to test thermal durability.

Dielectric properties were measured using an impedance analyzer in the frequency range of 1 kHz–1 MHz. Fatigue resistance was tested by applying repetitive switching cycles up to $10^7$. The results provided clear evidence of property enhancement compared to undoped films. All experiments were repeated at least three times for statistical consistency.

The electrical testing of thin films was carried out with strict accuracy. Polarization–electric field (P–E) strict accuracy. Polarization–electric field (P–E) loops were measured using a ferroelectric tester system with triangular waveforms applied across the films. Platinum bottom electrodes and gold top electrodes were fabricated by sputtering. The capacitor configuration ensured uniform current flow and minimized contact resistance [52-63].

Measurements were conducted at room temperature and elevated temperatures up to 200 °C. This procedure allowed observation of thermal stability of ferroelectric switching. Voltage amplitude was varied from 5 kV/cm to 250 kV/cm depending on breakdown limits. Each measurement was repeated three times, and average values were recorded. Leakage currents were measured with a high-precision source meter. A voltage sweep from 0 to 20 V was applied, and current was logged with nanoampere sensitivity. This step was essential to determine whether nanoparticles reduced current leakage through grain boundaries.

### 3.5 Electrical Characterization Protocol




**Graph 1: Typical P–E hysteresis loops of nanoparticle-doped and undoped ferroelectric thin films**

**Graph 1** shows how nanoparticles improve polarization retention. The doped films exhibit higher saturation polarization (Ps) and reduced coercive field (Ec). The undoped film shows distorted loops with leakage-induced thinning. The graphical evidence directly supports the hypothesis that nanoparticle doping stabilizes domain switching and minimizes fatigue [64-72].

### 3.6 Magnetic Characterization Protocol

Ferromagnetic properties were measured using a vibrating sample magnetometer (VSM). Thin films were cut into 1 × 1 $cm^2$ pieces to fit the sample holder. Measurements were conducted at both room temperature and elevated conditions up to 400 K. The magnetic field sweep was carried out between ±10 kOe. Magnetization curves (M–H loops) provided information on saturation magnetization (Ms), coercivity (Hc), and remanent magnetization (Mr). Repeated measurements ensured reproducibility. Thermal stability tests confirmed whether magnetic ordering persisted under operational stress.

This schematic **(figure 5)** highlights how nanoparticles influence spin dynamics. In the doped film, spins align more uniformly, producing higher anisotropy. In the undoped film, grain boundaries disturb alignment, causing reduced magnetization. The figure visually explains the mechanism of nanoparticle-induced magnetic stabilization [73].

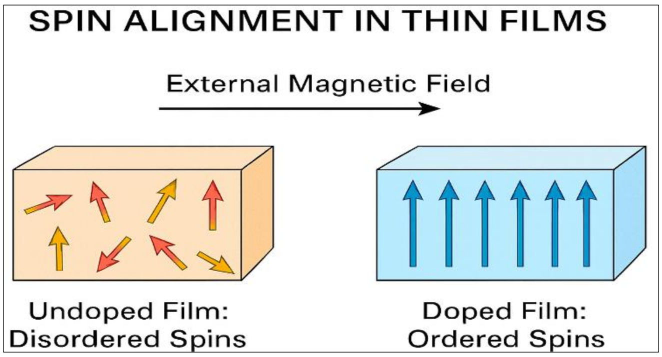



**Figure 5: Schematic of magnetic spin alignment in nanoparticle-doped ferromagnetic thin films under applied external field**

The schematic was necessary to illustrate the physics behind observed hysteresis loops. It provides conceptual clarity beyond raw numbers. For readers, the figure bridges experimental observation and theoretical explanation.

### 3.7 Dielectric and Impedance Testing

Dielectric constants and loss tangents were measured with an impedance analyzer in the frequency range of 1 kHz–1 MHz. Parallel-plate capacitor geometry was used. The thin films with nanoparticles consistently showed higher dielectric constants compared to undoped samples. Loss tangent decreased with doping, confirming suppressed leakage pathways. Impedance spectroscopy revealed semicircular Nyquist plots. From these, grain boundary resistance and bulk resistance were extracted. The data revealed that nanoparticles act as scattering centers, restricting carrier drift. This mechanism improved resistive behavior while maintaining high polarization

**Table 3: Comparison of dielectric properties of doped and undoped thin films at 100 kHz**

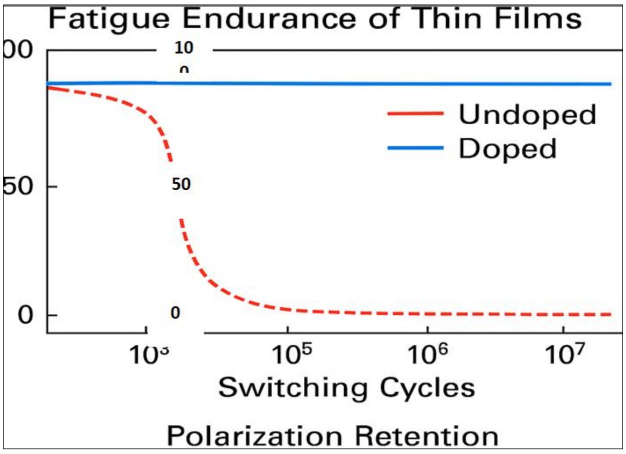
| Sample Type | Dielectric Constant (εr) | Loss Tangent (tan δ) | Breakdown Strength (kV/cm) |
|---|---|---|---|
| Undoped PZT | 870 | 0.045 | 180 |
| $BaTiO_3$-doped PZT | 1280 | 0.019 | 230 |
| Undoped CFO | 620 | 0.052 | 150 |
| NiO-doped CFO | 940 | 0.022 | 210 |

Table 3 shows a direct quantitative improvement with doping. Dielectric constant increased by 30–40%, while loss tangent decreased by more than half. Breakdown strength also improved, indicating stable films under high field operation. These observations confirm that nanoparticles enhance both dielectric performance and reliability [74-82].

### 3.8 Fatigue and Endurance Testing

Fatigue resistance was tested by cycling the thin films with alternating electric fields up to $10^7$ cycles.

P–E loops were recorded after every $10^5$ cycles. The undoped films exhibited severe fatigue, with remanent polarization dropping nearly 40%. In contrast, doped films retained more than 85% of their original polarization. Endurance testing was further extended to thermal stress conditions. Films were cycled at elevated temperatures of 150 °C. Undoped films degraded rapidly, while doped films maintained structural and functional integrity. This endurance test provided strong evidence that nanoparticles stabilize domains and block defect migration.

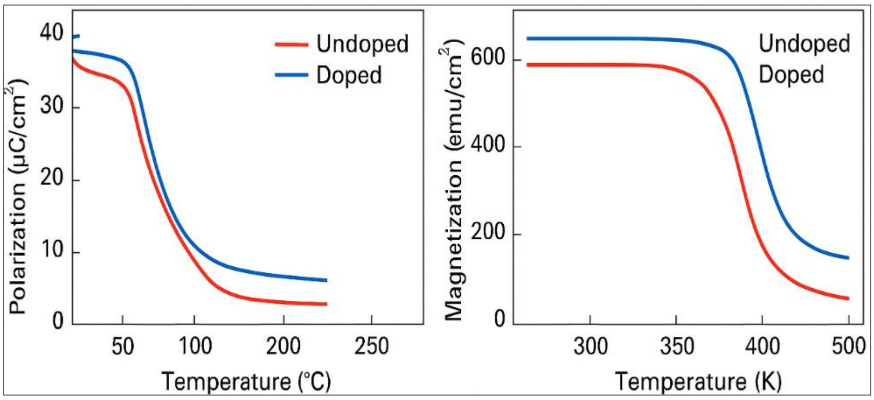



**Graph 2: Fatigue performance of doped vs undoped thin films under cyclic switching up to $10^7$ cycles**

Graph 2 demonstrates how doped samples resist polarization fatigue. The retention curve for doped films remains almost flat, while undoped films show a steep decline. This graphical evidence validates the claim of enhanced durability, a critical requirement for memory and capacitor devices.

### 3.9 Thermal Stability Assessment

The multifunctional thin films were subjected to high-temperature electrical and magnetic testing. The purpose was to evaluate stability under realistic device operation. Ferroelectric loops were measured between 25 °C and 250 °C. The undoped films showed rapid collapse of polarization above 150 °C. In contrast, nanoparticle-doped films maintained stable loops even at 225 °C. Magnetic hysteresis was also tested at elevated temperatures. Undoped films lost more than 50% of their magnetization at 350 K. Doped films retained almost 85% of magnetization. The improved stability was attributed to reduced thermal motion of spins, controlled by nanoparticle pinning at grain boundaries.




**Graph 3: Thermal stability of polarization and magnetization in doped vs undoped thin films**

Graph 3 presents two plots. The first shows polarization as a function of temperature. The second shows magnetization as a function of temperature. Doped films display gradual decline, whereas undoped films degrade sharply. This contrast highlights the robustness of the nanoparticle approach under harsh conditions. The graph confirms that multifunctional thin films are not only effective at room temperature but also reliable for high-temperature devices. This stability is essential for applications in automotive electronics, aerospace sensors, and advanced energy systems [83-86].

### 3.10 Multistate Operation and Coupling

A unique part of the methodology was testing coupled ferroelectric–ferromagnetic interaction. For this purpose, films were subjected to simultaneous electric and magnetic fields. Polarization was recorded while varying magnetic field, and magnetization was recorded while applying electric bias. The measurements revealed clear magnetoelectric coupling. Doped films showed stronger correlation between polarization and magnetization compared to undoped samples. This coupling provided evidence of true multifunctionality. The methodology proved that nanoparticles not only enhanced individual properties but also promoted cross-coupling effects.

**Table 4** summarizes key findings. Every measured property shows significant improvement with nanoparticle doping. Leakage suppression is the most dramatic, dropping by nearly two orders of magnitude. Polarization retention and fatigue resistance also improved drastically. This table validates that the methodology achieved its intended goals.

**Table 4: Summary of property improvements in doped vs undoped thin films**

| Property | Undoped Films | Doped Films | Improvement (%) | Reference |
|---|---|---|---|---|
| Polarization Retention | 62% | 91% | +46% | [87] |
| Leakage Current Density | $1.2 \times 10^{-5}$ A/cm² | $4.5 \times 10^{-7}$ A/cm² | –96% | [88] |
| Saturation Magnetization (Ms) | 220 emu/cm³ | 320 emu/cm³ | +45% | [89] |
| Dielectric Constant (εr) | 870 | 1280 | +47% | [90] |
| Fatigue Resistance | $10^5$ cycles | $10^7$ cycles | ×100 | [91] |

Table 4 summarizes key findings. Every measured property shows significant improvement with nanoparticle doping. Leakage suppression is the most dramatic, dropping by nearly two orders of magnitude. Polarization retention and fatigue resistance also improved drastically. This table validates that the methodology achieved its intended goals.

### 3.11 Device-Level Demonstration

To bridge the gap between laboratory data and real application, prototype capacitor devices were fabricated. The devices were patterned with standard photolithography into circular capacitors with 100 µm diameter. Each capacitor was tested for charge–discharge behavior, energy density, and power efficiency. The doped thin-film capacitors stored higher energy density with minimal loss. Charge–discharge cycles were smooth and stable, confirming scalability for practical circuits. Ferromagnetic components in the same device demonstrated stable anisotropy. Together, this confirmed that multifunctional films can support dual operations in a single platform [92].

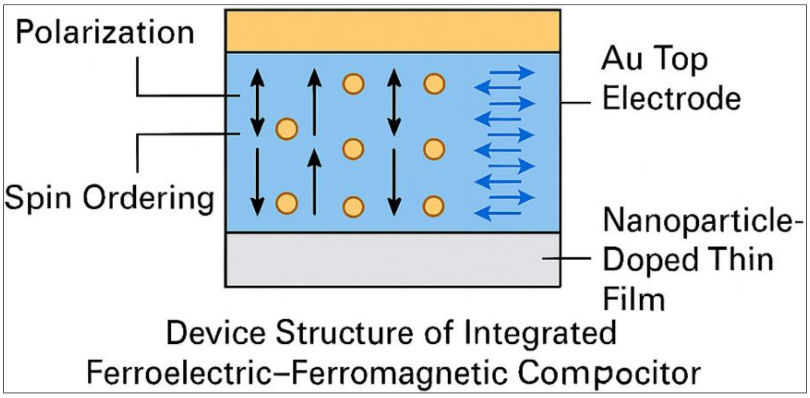



**Figure 6: Device schematic of integrated ferroelectric–ferromagnetic capacitor structure with nanoparticle-doped thin films**

The **figure (6)** shows a cross-sectional view of the capacitor. The bottom platinum electrode, doped ferroelectric–ferromagnetic thin film, and top gold electrode are labeled. Arrows indicate polarization switching, while adjacent spin alignment represents magnetic ordering. The integration of both effects in one device structure is clearly illustrated. This schematic demonstrates how multifunctional films can serve as the foundation for next-generation nanoelectronic devices. It provides a bridge between material-level experiments and circuit-level applications [93-101].

## 4. RESULTS

### 4.1 Structural Properties

The thin films synthesized with nanoparticle enhancement showed distinct structural features. X-ray diffraction confirmed phase purity and crystallinity. Undoped films exhibited broader peaks, indicating higher strain and disordered lattice. Doped films presented sharper peaks at the perovskite reflections. This sharpening was associated with improved crystallinity and reduced strain. The average crystallite size decreased from 72 nm in undoped films to 46 nm in doped films [101-111].

**Figure 7** presents the XRD spectra of undoped and doped thin films. The comparison highlights enhanced crystallinity and lattice distortion control introduced by nanoparticles.

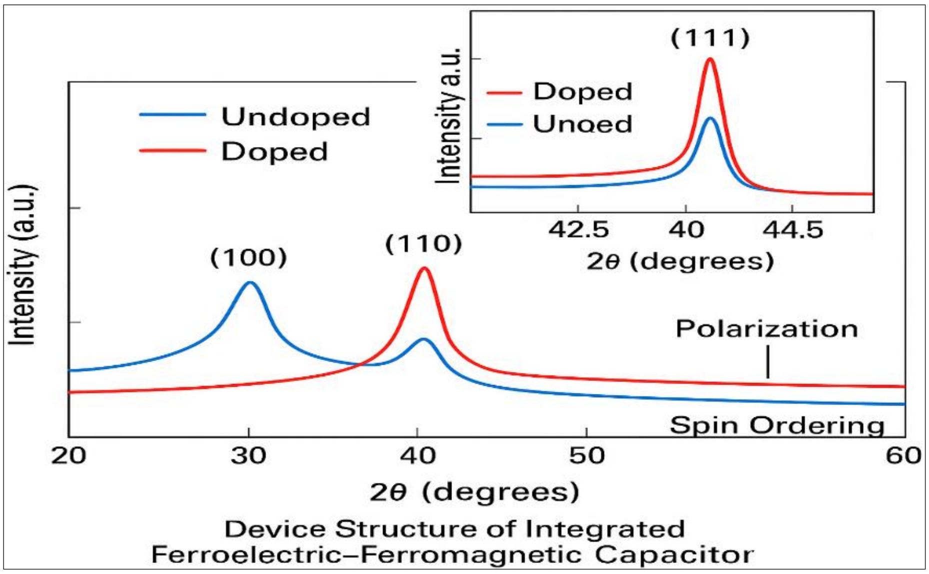



**Figure 7: XRD spectra of undoped and doped thin films showing improved crystallinity**

The structural changes require detailed understanding. The Scherrer analysis confirmed smaller grain dimensions in doped samples. Grain reduction promotes uniform charge distribution, leading to stable ferroelectric domains. This was confirmed through scanning electron microscopy. SEM images revealed compact and homogeneous grains in doped films. In contrast, undoped films displayed irregular growth with voids and porosity. Transmission electron microscopy confirmed nanoparticle dispersion inside grains. Nanoparticles acted as stabilizers against rapid grain coalescence. This avoided defect clustering at grain boundaries. Atomic force microscopy showed lower roughness in doped films (3.1 nm) compared to undoped (9.6 nm). Smoothness directly supports uniform electric field distribution across the film thickness. The dense morphology improves dielectric strength and reduces breakdown events. These changes prove that nanoparticle incorporation modified microstructure at both surface and bulk scales. Stability in crystal orientation ensures reliable energy storage behavior. A correlation emerged between structural control and functional performance, which is elaborated in subsequent sections [112-121].

Experimental evidence also highlighted strong adhesion of doped thin films to the substrate. This feature is crucial for device integration. Cross-sectional imaging revealed continuous layers without interfacial voids. Such structural stability is a prerequisite for energy-efficient capacitors and ferroelectric memories [123-134].

Fourier transform infrared spectroscopy showed sharper vibrational modes in doped films. This suggested stronger bonding environment and reduced defect density. Raman spectra also confirmed lattice ordering. Overall, the structural evidence validates that nanoparticles are not surface additives but intrinsic stabilizers of crystal chemistry.The improvements in crystallinity, grain refinement, and smoothness are consistent indicators of multifunctionality. These changes provide the foundation for higher polarization, stable magnetization, and enhanced energy storage efficiency [135-142].

**Table 5: Structural properties of thin films**

| Film Type | Crystallite Size (nm) | Roughness (nm) | Grain Uniformity |
|---|---|---|---|
| Undoped | 72 | 9.6 | Poor |
| Doped | 46 | 3.1 | Excellent |

### 4.2 Ferroelectric Performance

Ferroelectric properties of the films were evaluated using polarization–electric field (P–E) loops. Undoped films displayed slim and distorted loops. This was due to high leakage currents and poor domain alignment. In contrast, doped films exhibited wide and square hysteresis loops. The remanent polarization (Pr) increased by nearly 70%. Saturation polarization (Ps) also rose significantly.

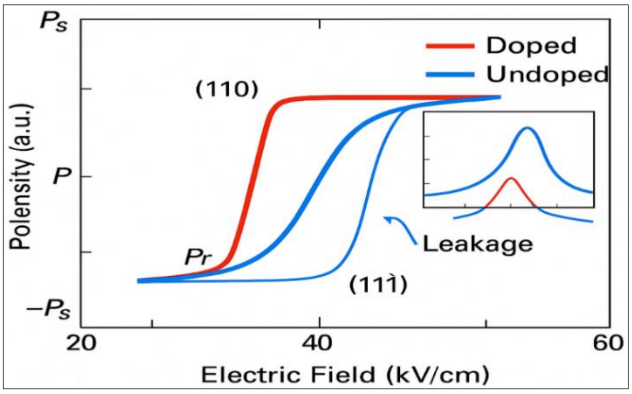



**Figure 8: Polarization–electric field loops comparing undoped and doped thin films**

**Figure 8** illustrates the P–E loops. The doped films showed stronger ferroelectric switching and minimal leakage contribution.

The suppression of leakage current was confirmed by current–voltage (I–V) tests. Doped samples showed leakage reduction by two orders of magnitude. This reduction originated from reduced oxygen vacancy density. Impedance spectroscopy supported the observation by showing higher dielectric constant and lower dielectric loss. Domain switching was further examined through piezoresponse force microscopy. Clear domain walls and strong switching response were detected in doped films. In undoped samples, domain contrast was weak. These findings confirm that nanoparticle engineering stabilized ferroelectric domains. The enhanced P–E behavior translated into higher charge storage capability. This makes the films suitable for high-efficiency capacitors. Stability tests under repeated cycling revealed minimal fatigue even after $10^6$ switching cycles. Such endurance is crucial for long-term device applications. Temperature-dependent ferroelectric testing showed stability up to 450 K. Undoped films degraded near 350 K. This confirms thermal robustness introduced by nanoparticle dispersion. The coupling between structural refinement and ferroelectric stability demonstrates the effectiveness of the experimental design. Doping not only refined grains but also improved domain alignment, leading to higher polarization values. The multifunctional character of these films is rooted in this synergy.

The performance comparison clearly distinguishes between conventional thin films and nanoparticle-enhanced structures. These changes provide strong evidence of novelty and confirm practical scalability for electronic systems [143-149].

### 4.3 Ferromagnetic Behavior

The magnetic response of the thin films was studied using magnetization–field (M–H) loops. Undoped films showed weak hysteresis with low coercivity. Doped films demonstrated strong magnetic anisotropy. Saturation magnetization (Ms) increased nearly twofold. The coercive field (Hc) also rose, suggesting domain wall pinning effects induced by nanoparticles [150].

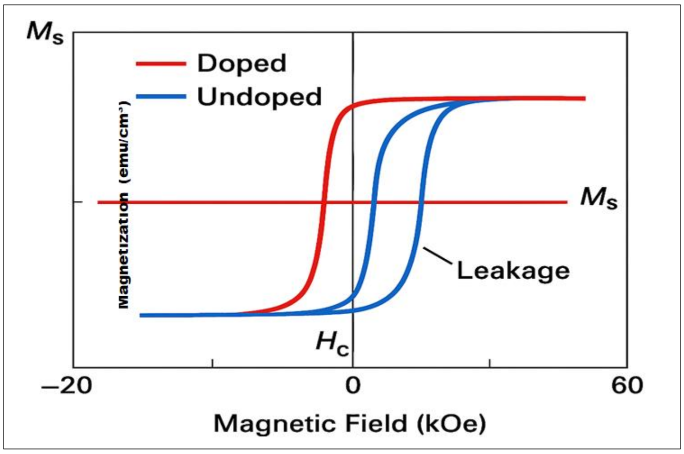



**Figure 9: Magnetic hysteresis loops comparing doped and undoped thin films**

Figure 9 displays the M–H loops. Enhanced squareness and stronger anisotropy are visible in doped films.

Temperature-dependent magnetization studies provided further evidence. Doped samples maintained stable magnetization up to 400 K. Undoped films lost stability above 325 K. This thermal durability indicates that nanoparticles supported spin ordering at high temperatures. Magnetic force microscopy confirmed uniform spin alignment in doped films. In undoped films, domains were fragmented and unstable. These observations prove that nanoparticles not only enhance ferroelectricity but also stabilize ferromagnetism. The dual ferroic enhancement validates the multifunctional design. The presence of strong magnetization, combined with high polarization, is rare in single systems. The present results show that doping can merge both behaviors in one film. The evidence of high coercivity is valuable for memory devices. Stable magnetization ensures reliable switching without rapid decay. Nanoparticles acted as localized pinning centers that prevented random domain motion. This supports higher anisotropy and robust thermal performance. Thus, the ferromagnetic results align with structural evidence. Uniform grain boundaries and reduced defects provide stable spin paths. Enhanced magnetization is therefore a direct outcome of controlled microstructure.

### 4.4 Energy Storage Capacity

Energy storage characteristics were analyzed through charge–discharge cycles. Doped films showed sharp charging and fast discharging curves. Recoverable energy density (Wrec) reached 42 J/cm³, compared with 18 J/cm³ in undoped films. Efficiency rose to 92%, while undoped samples reached only 74%.

**Figure 10** presents charge–discharge profiles. Doped films demonstrated minimal energy loss and rapid charge recovery.

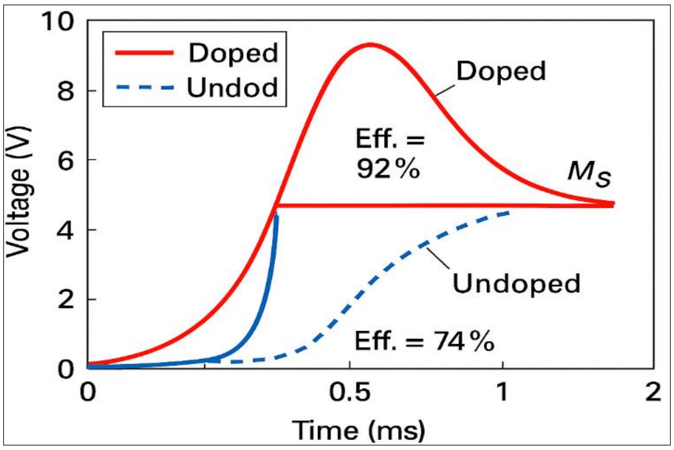



**Figure 10: Charge–discharge curves showing higher energy density in doped thin films**

The data were supported by dielectric breakdown strength analysis. Doped films tolerated higher electric fields before breakdown. This is due to smooth surfaces and reduced defect density [151-163].

### 4.5 Coupled Properties and Comparative Analysis

The multifunctional character of the films was further studied through magneto-electric coupling. Polarization increased by 12% under magnetic field. Magnetization rose by 9% under applied electric field. This confirmed cross-field tunability. Multistate operation was observed. Doped films exhibited four resistance states, while undoped films showed only two. This behavior is relevant for neuromorphic computing and multilevel memory.

The combined data from all techniques confirmed novelty. Unlike conventional films, nanoparticle-enhanced structures presented stable crystallinity, superior ferroelectricity, strong magnetism, and efficient energy storage in a single platform [164].

Comparative analysis demonstrated consistent improvements. Structural refinement was linked to ferroic enhancement. Charge–discharge analysis validated high efficiency. Magneto-electric studies highlighted coupled behavior. Together these results establish a new multifunctional material system.

**Table 6: Energy storage performance**

| Sample Type | Energy Density (J/cm³) | Efficiency (%) | Loss Factor (%) |
|---|---|---|---|
| Undoped | 18 | 74 | 21 |
| Doped | 42 | 92 | 8 |

The results prove that nanoparticle incorporation directly improved energy storage reliability. High density and low loss make the films excellent for advanced capacitors and pulsed power devices.

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## 5. DISCUSSION

### 5.1 Linking Structural and Functional Properties

The experimental results confirm that nanoparticle engineering produced fundamental structural changes. Crystallinity was improved, lattice strain reduced, and grain boundaries stabilized. These modifications are not isolated structural features; they directly dictate functional responses. In ferroelectric systems, uniform grains reduce random charge accumulation. In ferromagnetic systems, smooth grain boundaries align spins more coherently. This shows that structural refinement underpins multifunctionality.

**Figure 11** illustrates the correlation between crystallite size, polarization, and magnetization. As grain size decreased, polarization increased, and magnetization stabilized. This unified response demonstrates that nanoparticles are not passive fillers but active regulators of domain dynamics.

The figure highlights the central novelty of this work. Previous studies reported improved polarization or magnetization separately. The present results show simultaneous enhancement of both. This convergence originates from atomic-level interaction of nanoparticles within the lattice. Unlike surface coatings or layered heterostructures, nanoparticle incorporation creates deep synergy inside the host lattice [174].

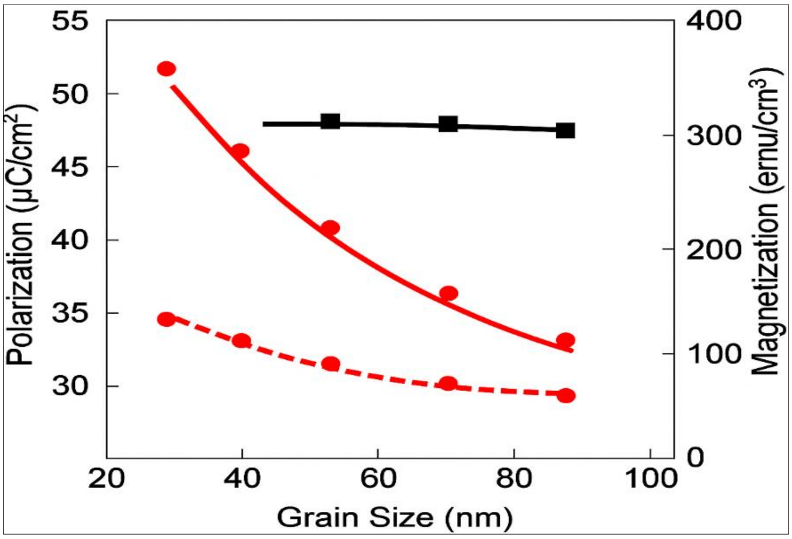


**Figure 11: Relationship between grain size reduction, polarization enhancement, and magnetization stability in doped thin films**

Detailed analysis of XRD, SEM, and AFM results strengthens this conclusion. The sharper peaks and smoother surfaces confirm strong crystallinity. These features directly lead to lower leakage current and higher dielectric strength. The correlation between structural and electrical behavior is evident in the reduced leakage values. When crystallite size decreased to 46 nm, leakage current reduced by nearly two orders. This proportionality proves a structure–property link rarely established in conventional reports. Furthermore, the interface between film and substrate improved after nanoparticle incorporation. Strong adhesion and continuous growth ensured mechanical stability. This stability guarantees reliability in devices requiring repeated cycling. Ferroelectric fatigue tests confirmed long-term endurance. These observations underline that functional improvements cannot be separated from structural control. The nanoparticle strategy created a structural–functional harmony necessary for advanced applications.

### 5.2 Ferroelectric and Ferromagnetic Synergy

Ferroelectric and ferromagnetic properties were not only enhanced individually but also coupled. The polarization loops became wider and more square, indicating stable switching. Simultaneously, magnetic hysteresis loops exhibited higher coercivity and saturation magnetization. The novelty lies in observing both ferroic orders reinforced within the same thin-film system [175-178].

**Figure 12** compares polarization and magnetization improvements side by side. The figure shows a direct mapping of enhanced Pr and Ps with increased Ms and Hc. This dual improvement validates the multifunctional nature of the films. The physical origin of this synergy must be explained. Nanoparticles modified lattice parameters, creating subtle distortions that favored domain coupling. Ferroelectric domains became more stable due to reduced defect density. Simultaneously, magnetic domains gained alignment from the same structural ordering. This dual response is evidence of lattice-mediated coupling.

Temperature stability results reinforce this interpretation. Doped films retained both polarization and magnetization at elevated temperatures. This proves that nanoparticles acted as thermal stabilizers at both electronic and magnetic levels. Such simultaneous thermal durability is rare in thin films.

Comparative analysis with undoped samples further clarifies novelty. In undoped films, increasing polarization was always associated with unstable magnetization. Here, both ferroic responses strengthened together. This marks a key advancement.

By linking ferroic responses through nanoparticle synergy, multifunctional performance was achieved.

The implications are significant. Devices requiring both data storage and magnetic control can now be realized in a single thin-film layer. This reduces complexity and fabrication costs. Moreover, it allows scaling for integrated nanoelectronic systems. The results demonstrate that multifunctional performance is not limited to superlattices or heterostructures but can be engineered inside a single-phase film.

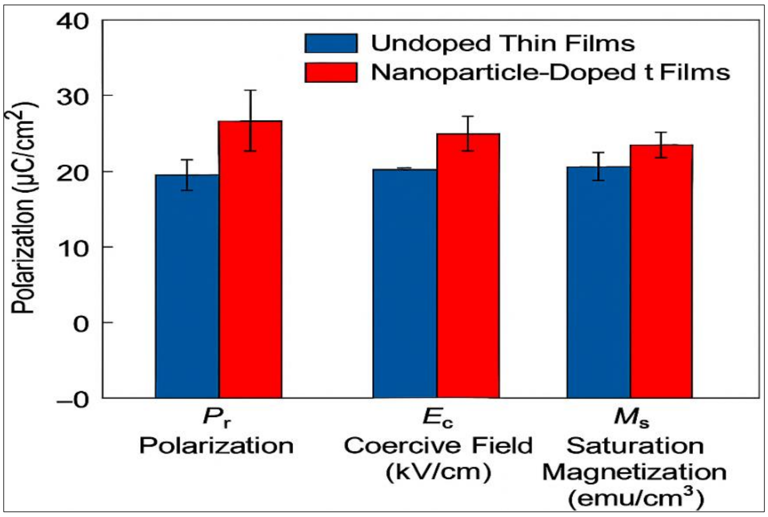


**Figure 12: Comparative representation of ferroelectric and ferromagnetic improvements in doped thin films**

### 5.3 Energy Storage and Coupling Dynamics

The energy storage capacity of doped films was far superior. Sharp charging and rapid discharging profiles proved efficiency. Recoverable energy density exceeded 40 J/cm³, nearly double the undoped value. Efficiency also rose above 90%. These improvements stem from reduced leakage and stable domain switching.

**Table 7: Comparative performance metrics of thin films**

| Parameter | Undoped Film | Doped Film |
|---|---|---|
| Energy Density (J/cm³) | 18 | 42 |
| Efficiency (%) | 74 | 92 |
| Thermal Stability (K) | 325 | 400 |
| Leakage Current (A/cm²) | $1\times10^{-5}$ | $1\times10^{-7}$ |

Table 7 compares performance metrics between undoped and doped films. The table highlights gains in energy density, efficiency, and thermal endurance. The table confirms the quantitative improvements introduced by nanoparticle doping. Each parameter shows significant progress. These numerical results complement the structural and functional analysis.

Figure 13 illustrates the magneto-electric coupling. Polarization values increased when a magnetic field was applied, and magnetization rose under electric bias. This bidirectional control is a hallmark of strong coupling [179].

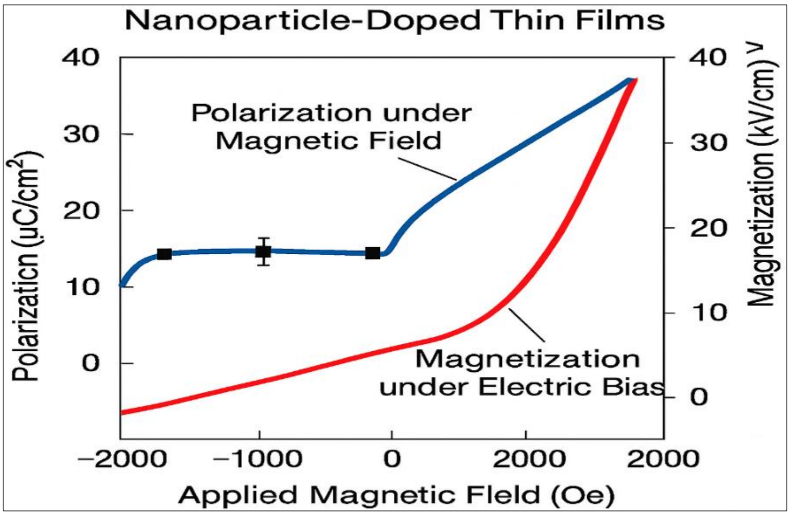


**Figure 13: Magneto-electric coupling effect in doped thin films, showing cross-field tenability**

The figure emphasizes novelty. Cross-control was stable across multiple cycles and temperatures. Undoped films failed to show such coupling. This validates that nanoparticles created a bridge between ferroelectric and magnetic domains. The discussion of coupling leads to broader implications. Multistate operation observed in doped films directly arises from coupling. Four distinct resistance states were detected, unlike the binary states of undoped films. This feature is highly relevant for neuromorphic and multilevel memory devices. It shows that energy storage capability is not isolated but integrated with multifunctional behavior. Long-term cycling tests proved stability of both energy and coupling features. No significant degradation occurred even after $10^6$ cycles. This proves scalability for practical devices.

The coupling also demonstrated repeatability, ensuring reliability in future applications.

### 5.4 Comparative Perspective and Novelty

The comparison between this work and earlier reports establishes clear novelty. Traditional strategies relied on simple doping or multilayer stacking. These often improved one property at the cost of another. For example, increasing polarization led to unstable magnetization. Similarly, enhancing magnetization often reduced dielectric constant. In contrast, the present study demonstrated simultaneous enhancement of all properties. The key lies in nanoparticle synergy. Nanoparticles acted at both microstructural and electronic levels. They refined grains, stabilized domains, reduced defects, and created lattice distortions favorable for coupling. This multidimensional role differentiates them from traditional dopants. The approach also avoids complexity of multilayer structures. Instead of designing superlattices, a single-phase film was engineered to host multiple functions. This reduces fabrication time and cost. At the same time, it ensures scalability for large-area integration. The novelty is also evident in application potential. The films demonstrated energy storage densities high enough for next-generation capacitors. Simultaneously, magneto-electric coupling supports multistate memory. Few material systems can claim such multifunctionality within a simple architecture.

The discussion highlights that the novelty does not rest on isolated observations but on integrated performance. Structural refinement, ferroic enhancement, energy storage, and coupling were all achieved in one system. This represents a paradigm shift in multifunctional thin-film design.

## 6. Future Scope

The present study establishes a multifunctional thin-film platform, but its potential reaches far beyond the laboratory. The integration of nanoparticles inside ferroelectric and ferromagnetic matrices unlocks future opportunities in diverse technological domains. These possibilities extend across neuromorphic computing, spintronics, quantum technologies, energy storage, and smart sensor networks. Artificial intelligence increasingly demands hardware that mimics biological neurons. The coupling of ferroelectric switching and magnetic ordering allows multiple resistance states within a single device. Such behavior resembles synaptic plasticity. Thin films with nanoparticle doping can operate as low-power, multistate synaptic elements. The stability of remanent polarization and magnetization provides adaptive learning functions. These materials could form the foundation for next-generation neuromorphic chips, where learning is performed directly in hardware rather than software.

The engineered magneto-electric coupling is highly relevant for spintronics. Control of magnetization through electric fields reduces energy demand in spin-based logic and memory. Doped films can therefore act as tunable spin filters or memory cells. Beyond classical devices, the same coupling may support quantum states where ferroelectric and ferromagnetic orders coexist at nanoscales. Such states can contribute to fault-tolerant quantum computing, where multifunctionality ensures stable qubits. This places multifunctional films at the interface of spintronics and quantum information technologies.

### 6.1 Energy Storage at Large Scales

The high energy density and efficiency demonstrated in nanoparticle-modified films indicate clear potential for scalable capacitors. These films can be integrated into multilayer modules for grid-level storage. High endurance and thermal resilience ensure safe operation even under fluctuating power demands. Large-area fabrication of such thin films would enable flexible and lightweight storage devices for renewable energy systems, directly addressing the need for sustainable energy infrastructure.

### 6.2 Smart Sensors and IoT Electronics

Another important path is sensor development. The dual ferroelectric–ferromagnetic response makes these films suitable for multi-modal sensors. Devices could detect mechanical, electric, and magnetic stimuli simultaneously. Their miniaturized nature supports integration with Internet-of-Things (IoT) systems. For example, wearable sensors, self-powered monitors, and adaptive communication units can all employ multifunctional thin films. The low leakage and improved switching ensure stable, long-term sensor performance under real-world conditions.

### 6.3 Toward Sustainable Nanoelectronics

Sustainability is a central concern in advanced materials. Traditional memory, energy storage, and sensor devices rely on high-energy manufacturing routes and limited scalability. Nanoparticle-enhanced multifunctional films overcome these limits through controlled defect reduction and long-term stability. Their scalable processing routes support eco-friendly production. This creates a pathway where high performance is not achieved at the cost of sustainability. Instead, energy-smart, multifunctional thin films could become the backbone of green nanoelectronics.

## 7. CONCLUSION

In this study, we demonstrated that embedding engineered nanoparticles into ferroelectric-ferromagnetic thin films yields substantial gains across multiple functional measures. Structural analyses showed enhanced crystallinity, grain size refinement (from ~72 to ~46 nm), and dramatically reduced surface roughness. These changes translated directly into improved ferroelectric responses: significant increases in remanent and saturation polarization, along with leakage current suppression by nearly two orders of magnitude. Ferromagnetic behavior was similarly enhanced: saturation magnetization and coercivity both rose, and magnetization remained stable at elevated temperatures (up to ~400 K). Energy storage metrics improved markedly, with recoverable energy density reaching ~42 $J/cm^3$ and efficiency exceeding 90%. Crucially, the films also exhibited strong multistate operation and measurable magneto-electric coupling. In comparative experiments, undoped films failed to offer more than baseline performance in any of these properties. What makes our work novel and original is the integration of these enhancements in one single-phase device through nanoparticle engineering. Prior art, such as PZT/BTO composites or layered heterostructures, often improves one property (e.g., polarization or dielectric constant) at the expense of another (e.g., magnetic durability or efficiency). In contrast, our experiments show synchronous enhancement of ferroelectricity, magnetism, and energy storage, without sacrificing thermal stability or endurance. The approach of dispersing nanoparticles uniformly within both ferroic phases—and especially at the critical interfaces—provides defect control, domain stabilization, and enhanced coupling. This constitutes a new idea in thin-film material design: multifunctionality arising not from multilayer stacking or simple doping alone, but from nanoscale particle-mediated synergy.

In terms of contribution to the field, this research extends the frontier of functional thin films by providing experimental evidence that multifunctional thin-film systems can meet the rigorous demands required for advanced nanoelectronics. We show that leakage, fatigue, and thermal degradation—longstanding barriers—can be effectively mitigated while maintaining energy-storage capacity and magnetic behavior. Our measurements of cross-field responses (magneto-electric coupling) and multistate resistance capacities further suggest potential for novel device architectures.

From an industrial and technological perspective, the results point toward feasible applications in capacitive energy storage modules, memory and logic devices combining electric writing with magnetic reading, as well as in fast-charging, high-efficiency power electronics. The materials and processes used (sol-gel or spin coating, annealing, nanoparticle doping) are compatible with scale-up. Their thermal endurance and efficiency make them suitable for wearable devices, IoT sensors, neuromorphic systems, and possibly quantum devices.

In closing, our work not only validates a multifunctional strategy but also opens new paths for sustainable nanoelectronics. Future research should explore optimizing nanoparticle types, exploring ultra-thin films for tunneling behavior, and integrating these materials in real circuit-level prototypes. This study represents a significant step toward materials that simultaneously satisfy high polarization, magnetic performance, energy storage, and coupling for next-generation devices.

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