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Sustainable Perovskite Multiferroic Materials for Memristive Memory and Neuromorphic Computing Devices

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Abstract: Perovskite multiferroic materials, characterised by their unique coupling of ferroelectricity, magnetism, and additional functionalities, have emerged as promising candidates for next-generation electronic devices. Their potential is particularly significant in memristive memory and neuromorphic computing, where energy efficiency, multifunctionality, and compactness are critical. This abstract explores the role of perovskite multiferroics in enabling sustainable, high-performance memory and computing devices. Emphasis is placed on materials like $BiFeO_3$ and lead-free alternatives, demonstrating robust ferroelectric and magnetoelectric properties. Key topics include the mechanisms underpinning memristive behaviour, the integration of multiferroics in artificial synapses for neuromorphic computing, and sustainable fabrication techniques. Challenges such as scalability, thermal stability, and environmental impact are addressed, focusing on strategies for overcoming these hurdles. By leveraging sustainable synthesis methods and innovative device architectures, perovskite multiferroics present a transformative path toward eco-friendly, efficient, and multifunctional technologies for the future of electronics.
Keywords: Perovskite Multiferroics, Memristive Memory, Neuromorphic Computing, Sustainable Materials, Magnetoelectric Coupling.

I. INTRODUCTION

The modern world is increasingly driven by data-intensive applications, requiring advanced memory and computing systems that are efficient, compact, and sustainable. Traditional silicon-based technologies face challenges in scaling down, meeting the demands of energy efficiency, and addressing environmental concerns [1]. This has fueled the search for novel materials and architectures that can overcome these limitations while aligning with global sustainability goals [2]. Perovskite multiferroic materials have emerged as promising candidates in this context. These materials exhibit multiple ferroic properties, such as ferroelectricity, magnetism, and their coupling, enabling multifunctionality within a single platform [3]. Their inherent properties make them ideal for innovative device applications, including memristive memory, which is central to next-generation data storage [4], and neuromorphic computing, which aims to emulate the efficiency and adaptability of the human brain [5]. Furthermore, the sustainability of electronic materials and devices has become a critical consideration, as the electronics industry seeks to minimize its environmental footprint [6]. Incorporating eco-friendly synthesis methods, recycling strategies, and abundant raw materials is imperative to achieving this goal [7]. The potential of perovskite multiferroic materials as sustainable solutions for the future of electronics. It examines their structural and functional attributes, highlights their application in memristive memory and neuromorphic computing devices, and addresses the challenges associated with their development [8]. By combining sustainability with advanced material functionality, perovskite multiferroics pave the way for a greener and smarter technological era.

A. Overview of the Growing Need for Sustainable, Energy-Efficient Electronic Materials

The global demand for electronic devices has surged in recent years, driven by advancements in fields such as artificial intelligence, the Internet of Things (IoT), and high-performance computing [9]. As the proliferation of smartphones, laptops, data centres, and emerging technologies like electric vehicles continues, the environmental and economic impact of producing and powering these devices has become a critical concern [10]. The electronics industry currently consumes vast energy and relies heavily on resource-intensive materials, including rare-earth elements and hazardous chemicals [11]. These factors contribute to increased carbon emissions, environmental degradation, and supply chain vulnerabilities. There is a growing imperative to transition toward sustainable and energy-efficient materials and manufacturing processes [12].

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Sustainable materials not only minimize the environmental footprint but also enable long-term viability by reducing reliance on finite resources [13]. Energy efficiency, on the other hand, helps address the increasing power demands of modern electronic devices, which are often limited by heat dissipation and energy costs [14]. Traditional silicon-based technologies, while ubiquitous and cost-effective, face fundamental challenges in meeting these demands [15]. Issues such as scaling limits (the end of Moore's Law), power density constraints, and the environmental impact of silicon processing have spurred researchers to explore alternative materials [16]. These alternatives must satisfy a delicate balance of high performance, environmental compatibility, and economic feasibility. In this advanced functional materials like perovskite multiferroics have gained attention [17]. Their ability to combine multiple functionalities, such as ferroelectricity and magnetism, offers the potential for compact and energy-efficient device architectures [18]. Furthermore, advances in material synthesis and processing have paved the way for these materials to be manufactured more sustainably [19]. By integrating such materials into future technologies, the electronics industry can take a significant step toward addressing both environmental and performance challenges [20].

B. Brief Introduction to Perovskite Multiferroic Materials and Their Unique Properties

Perovskite multiferroic materials represent a fascinating class of materials with a wide range of applications in modern electronics [21]. Defined by their perovskite crystal structure (ABX_3), these materials derive their name from the mineral perovskite (calcium titanate, $CaTiO_3$) [22]. In this structure, the A-site typically hosts a larger cation (e.g., rare-earth or alkaline-earth metals), the B-site accommodates a smaller transition metal cation, and the X-site is occupied by an anion, commonly oxygen [23]. The resulting arrangement provides a highly versatile framework that can exhibit a variety of ferroic properties.
Multiferroics apart is their ability to exhibit two or more primary ferroic orders simultaneously, such as:

1) Ferroelectricity: The presence of a spontaneous electric polarization that can be reversed by an applied electric field [24].
2) Magnetism: Includes ferromagnetism, antiferromagnetism, or ferrimagnetism, arising from the magnetic ordering of spins in the material [25].
3) Magnetoelectric Coupling: A unique property where the magnetic and electric properties interact, enabling control of one property via the other [26]. The interplay of these properties makes perovskite multiferroics highly appealing for multifunctional devices. For example, in devices requiring memory storage, ferroelectricity can store information as electric polarization states, while magnetic properties enable non-volatile memory functionalities [27]. Furthermore, the coupling between these properties allows the development of devices with enhanced flexibility, such as those that can be written electrically and read magnetically [28]. One of the most widely studied multiferroic perovskites is bismuth ferrite ($BiFeO_3$), which demonstrates robust room-temperature ferroelectricity and antiferromagnetism [29]. Its ability to maintain these properties under ambient conditions has driven significant interest in practical applications [30]. Beyond their functional versatility, perovskite multiferroics are also structurally tunable. By modifying the composition or introducing defects, their properties can be tailored to suit specific applications [31]. This tunability, coupled with advances in sustainable synthesis techniques, positions them as a leading candidate for environmentally friendly and energy-efficient technologies [32].

C. Relevance of These Materials in Advancing Memory and Neuromorphic Computing Technologies

The growing demands for higher data processing speeds, lower power consumption, and compact device architectures have spurred significant advancements in memory and neuromorphic computing technologies [33]. Perovskite multiferroic materials, with their unique combination of ferroelectricity, magnetism, and magnetoelectric coupling, are exceptionally well-suited to address these requirements and drive innovation in these fields [34].

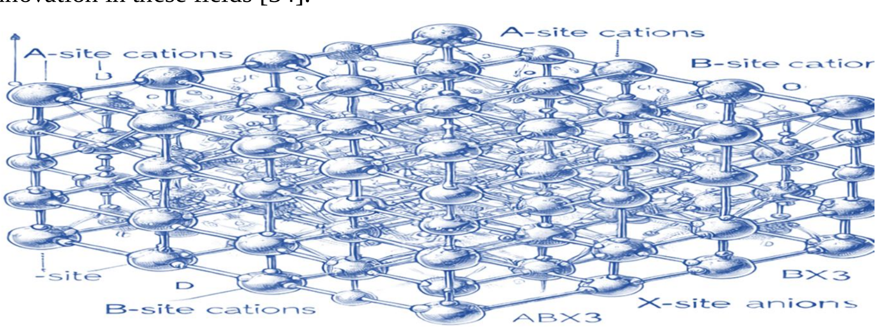

Figure 1: Crystal structure of a perovskite material, showcasing A-site, B-site, and X-site components.

II. UNDERSTANDING PEROVSKITE MULTIFERROICS

A. Basic Structure and Composition of Perovskites (ABX_3 Formula)

Perovskite materials are defined by their crystalline structure, which follows the general formula ABX_3 [35]. Figure 1 shows the crystal structure of a perovskite material (ABX_3 formula) with labelled A-site, B-site, and X-site positions. It provides a clear 3D perspective, showing the octahedral cage formed by X-site anions around the B-site cation.

1) A-Site Cations: Occupying the corners of the unit cell, these are larger cations, such as alkaline-earth (e.g., Ba^{2+}, Sr^{2+}) or rare-earth elements (e.g., La^{3+}, Pr^{3+}) [36].B-Site Cations: Smaller transition metal ions, such as Ti^{4+}, Mn^{3+}, or Fe^{3+}, occupy the centre of the unit cell and are surrounded by an octahedral framework of anions [37].
2) X-Site Anions: Typically oxygen, the anions form the octahedral network around the B-site cations, contributing to the overall stability and functionality of the structure [38]. This structure is inherently versatile, allowing substitution at both A- and B-sites. Such substitutions significantly influence the material's electrical, magnetic, and mechanical properties, making perovskites highly adaptable for a range of applications. The ability to manipulate lattice parameters and introduce defects further enhances their tunability [39].

B. Properties: Ferroelectricity, Magnetism, and Magnetoelectric Coupling

Perovskite multiferroics are particularly valued for their multifunctional ferroic orders, which often coexist and interact within a single material system:

1) Ferroelectricity:
   i. The spontaneous electric polarisation of the material can be reversed by applying an external electric field [40].
   ii. This property arises due to non-centrosymmetric distortions, where the central B-site cation shifts within its octahedral cage [41].
   iii. Applications: Non-volatile memory, sensors, and energy storage [42].
2) Magnetism:
   i. Magnetic ordering, including ferromagnetism, antiferromagnetism, or ferrimagnetism, arises from the spin alignment of electrons in the B-site transition metal ions [43].
   ii. The coupling of spins across the lattice is often mediated by superexchange interactions involving the oxygen anions [44].
   iii. Applications: Data storage, spintronics, and magnetic field sensors.
3) Magnetoelectric Coupling:
   i. The unique interaction between magnetic and electric orders allows for controlling magnetic properties via electric fields and vice versa.
   ii. This coupling is critical for developing multifunctional devices like magnetoelectric sensors and hybrid memory systems [42]. The coexistence and coupling of these properties make perovskite multiferroics ideal candidates for applications requiring energy-efficient and compact devices.

C. Examples of Prominent Perovskite Materials and Their Attributes

1) Bismuth Ferrite ($BiFeO_3$):
   i. One of the most widely studied multiferroic materials due to its room-temperature ferroelectricity and antiferromagnetism [18].
   ii. Attributes: High ferroelectric polarisation, strong magnetoelectric coupling, and robust environmental stability.
   iii. Applications: Non-volatile memory, sensors, and photovoltaic devices [45].
2) Lead-Free Perovskites:
   i. Examples: $BaTiO_3$, $Na_{0.5}Bi_{0.5}TiO_3$, and $K_{0.5}Na_{0.5}NbO_3$.
   ii. Attributes: Environmentally friendly alternatives with excellent ferroelectric properties, often tuned through doping or compositional adjustments [46].
   iii. Applications: Energy storage, piezoelectric actuators, and memory devices.
3) Rare-Earth-Based Perovskites (e.g., $TbMnO_3$):
   i. Exhibit strong magnetoelectric coupling and multiferroic behaviour at low temperatures.
   ii. Attributes: Tunable magnetic and dielectric properties, especially under strain or external fields [47].

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iii. Applications: Spintronics, quantum computing, and magnetoelectric sensors [48]. The combination of structural flexibility, intrinsic multifunctionality, and compatibility with sustainable fabrication techniques positions perovskite multiferroics as pivotal materials for the future of electronics. Their unique properties continue to drive innovation across fields such as memory technologies, neuromorphic computing, and renewable energy systems [49].

III. APPLICATIONS IN MEMRISTIVE MEMORY

A. Explanation of Memristors and Their Role in Non-Volatile Memory

Memristors, or memory resistors, are two-terminal devices that exhibit a relationship between charge and magnetic flux, enabling them to "remember" resistance states even after power is turned off [50]. This non-volatile memory characteristic makes them a promising alternative to traditional storage technologies like flash memory [51]. Memristors operate by manipulating resistance states through the movement of ions or defects, such as oxygen vacancies, within the device [52]. These states represent binary (or multilevel) data, making memristors suitable for high-density storage applications [53]. Additionally, their small size, low latency, and scalability align with the demands of modern electronic systems [54]. Applications of memristors extend beyond storage to include logic circuits and neuromorphic systems, where their ability to mimic synaptic behaviour in neural networks plays a critical role in energy-efficient computing.

B. How Multiferroic Materials Enhance Memristor Performance

Integrating multiferroic materials into memristors provides several performance advantages. Table 1 highlights key differences among these materials in terms of their properties and sustainability.

Table 1: Comparison of material properties of $BiFeO_3$, $BaTiO_3$, and $PbTiO_3$.

Material	Ferroelectricity ($\mu C/cm^2$)	Magnetoelectric Coupling	Thermal Stability (°C)	Environmental Sustainability
$BiFeO_3$	60	Strong	825	High (Lead-free)
$BaTiO_3$	26	Weak	120	High (Lead-free)
$PbTiO_3$	40	Moderate	490	Low (Lead)

1) Multifunctionality: The inherent ferroelectric and magnetic properties of multiferroics enable new modes of data storage and retrieval, such as electric field-driven magnetic switching [55].
2) Magnetoelectric Coupling: This property allows the control of resistance states through both electric and magnetic fields, enhancing the flexibility and robustness of memristors [56].
3) Defect-Driven Conductivity: Oxygen vacancies in perovskite multiferroics contribute to resistance switching, providing the foundation for stable and reproducible memory states [57]. By leveraging these properties, multiferroic-based memristors exhibit faster switching speeds, lower energy consumption, and higher endurance compared to conventional designs [58].

C. Benefits of Using Perovskites in Memristive Memory

1) Fast Switching

i. The high mobility of ions in perovskite multiferroics facilitates rapid transitions between resistance states [59].
ii. This speed is critical for applications requiring high data throughput [60].

2) Low Power Consumption:

i. Ferroelectric switching in perovskites requires minimal energy compared to purely electronic processes in traditional materials [61].
ii. This efficiency is especially beneficial for battery-powered and portable devices [62].

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3) Multilevel Resistance States

i. The ability to tune resistance across multiple levels enables higher storage densities [63].

ii. This feature supports advanced applications like data compression and machine learning, where multilevel data representation is essential [64].

4) Scalability

iii. Perovskites' structural versatility allows for miniaturization without compromising performance, aligning with the trend toward smaller and more integrated devices [65].

D. Sustainable Approaches to Fabricating Multiferroic-Based Memristors

The environmental compatibility of multiferroic-based memristors, researchers are exploring sustainable fabrication techniques:

1) Green Synthesis Methods: Techniques such as sol-gel, hydrothermal, and chemical vapour deposition (CVD) enable the production of high-quality multiferroic films with reduced chemical waste and energy consumption [66].

2) Lead-Free Materials: Replacing lead-based perovskites with environmentally friendly alternatives like $BaTiO_3$ or $BiFeO_3$ reduces toxicity concerns [67]. Figure 2 Flowchart showing eco-friendly fabrication techniques for multiferroic-based memristors, including recycling and low-temperature synthesis.

3) Recycling and Reusability: Recovery and recycling of critical raw materials, such as rare earths, ensure a sustainable supply chain [68].

4) Energy-Efficient Processing: Lower-temperature synthesis processes reduce the carbon footprint associated with device fabrication [69]. By combining these sustainable approaches with the inherent advantages of perovskite multiferroics, memristive memory devices can achieve high performance while aligning with global sustainability goals [70]. Such innovations position these devices as a cornerstone of the next generation of electronic technologies [71].

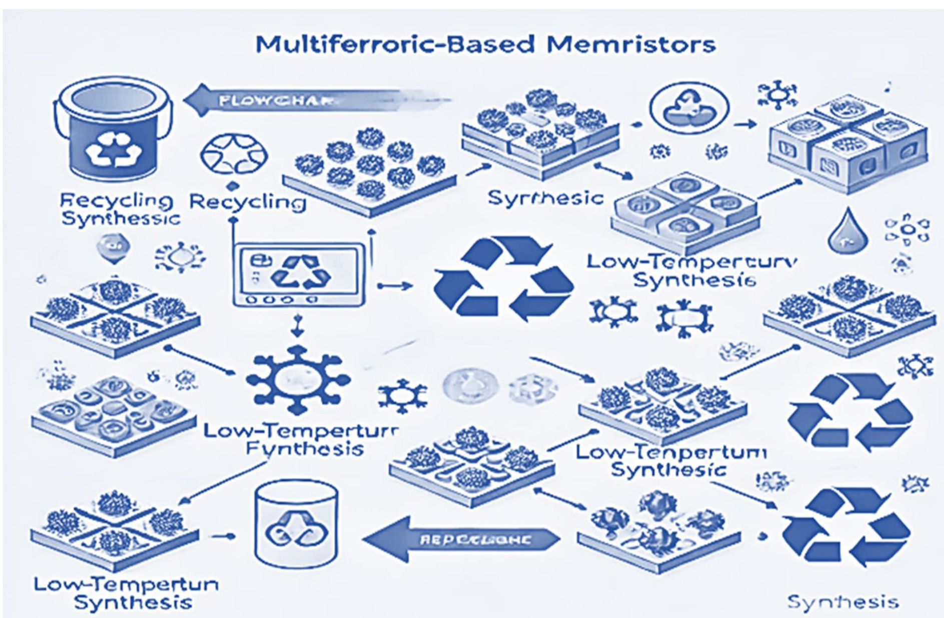

Figure 2: Flowchart showing eco-friendly fabrication techniques for multiferroic-based memristors, including recycling and low-temperature synthesis.

IV. APPLICATIONS IN NEUROMORPHIC COMPUTING

A. Overview of Neuromorphic Computing and the Need for Artificial Synapses:

Neuromorphic computing is a computational paradigm inspired by the architecture and function of the human brain. Unlike traditional computing systems, which rely on sequential operations and centralized processing units (like CPUs), neuromorphic systems aim to replicate the parallel, distributed, and adaptive nature of biological neural networks. This approach is particularly useful for tasks such as pattern recognition, decision-making, and learning, which require the processing of vast amounts of sensory data in real time [72].

1) Characteristics of Neuromorphic Computing:
   i. Parallel Processing: In biological systems, multiple neurons work simultaneously to process and transmit information. Neuromorphic computing mimics this behaviour by using networks of artificial neurons and synapses that operate in parallel, allowing for efficient data processing [73].
   ii. Energy Efficiency: The brain is highly energy-efficient, performing complex tasks while consuming only a fraction of the power of traditional supercomputers. Neuromorphic systems aim to replicate this energy efficiency, especially in edge computing devices and AI systems operating in resource-constrained environments [74].
   iii. Learning and Adaptation: Biological systems exhibit the ability to learn from experience, adjust to changing inputs, and make decisions based on past events. Neuromorphic systems incorporate similar learning mechanisms, often based on synaptic plasticity [75].
2) The Role of Artificial Synapses in Neuromorphic Computing:

Artificial synapses replicate the function of biological synapses by allowing for the dynamic modification of the "synaptic weight," essential for the system to learn from new inputs and adjust its behaviour. Key features include synaptic plasticity, non-volatility, and bidirectional modulation, typically implemented using memristors or resistive switching devices, with perovskites showing significant advantages for this purpose [76].

B. Role of Perovskite Multiferroics in Mimicking Synaptic Behavior

Perovskite multiferroic materials combine ferroelectricity, magnetism, and magnetoelectric coupling, offering exceptional potential for mimicking synaptic functions like modulation and information storage [77]. This section explores their applications in neuromorphic computing:

1) Ferroelectricity and Synaptic Weight Modulation: Perovskites like $BiFeO3$ exhibit spontaneous polarization that can be reversed with an external electric field, enabling the storage and adjustment of synaptic weights [78].
2) Magnetoelectric Coupling for Bidirectional Modulation: The coupling of electric and magnetic properties in perovskites allows for bidirectional modulation of synaptic strength, closely mimicking biological synapses [79].
3) Non-Volatility and Memory Retention: Perovskites exhibit non-volatile behaviour, meaning learned states remain stable even when power is removed, mimicking long-term memory in biological systems [80].

C. Advantages: Analog Switching, Energy-Efficient Operations, and Multifunctionality

Perovskite multiferroics offer analogue switching, low power consumption, and multifunctionality, making them ideal for neuromorphic systems. These advantages enable more accurate learning and processing, critical for tasks like speech recognition, image processing, and real-time decision-making [81].

D. Current Challenges in Integrating Multiferroics into Neuromorphic Devices

Despite the promising properties of perovskite multiferroics, several challenges remain in their integration into neuromorphic devices:

1) Material Synthesis and Quality Control: Variations in synthesis can affect material performance, requiring better control over processes and compositions [82].
2) Scalability and Integration with CMOS Technology: Scaling up perovskite materials for large-scale systems and integrating them with conventional CMOS technology remains a significant challenge [83].
3) Device Stability and Reliability: Environmental sensitivity and cyclic degradation can affect the long-term performance of perovskite-based devices, requiring research into more stable compositions and protective coatings [84].
4) Interface and Contact Issues: The interfaces between perovskites and other materials can hinder efficient operation, requiring better interface engineering and electrode materials [85].

Perovskite multiferroics hold tremendous potential for neuromorphic computing, offering properties that mimic the synaptic behaviour of biological systems. However, addressing challenges in material synthesis, scalability, and device stability is crucial for their successful integration into real-world applications. Continued research and development are essential for unlocking their full potential [86].

V. SUSTAINABILITY IN MULTIFERROIC MATERIALS

A. *Importance of Eco-Friendly Synthesis Methods (e.g., Sol-Gel, Hydrothermal Processes)*

Sustainability is a critical consideration in the development of new materials, especially as industries and research strive to minimize their environmental impact. In the context of multiferroic materials, including perovskites, the choice of synthesis method plays a significant role in determining the overall sustainability of these materials. Eco-friendly synthesis methods, such as sol-gel and hydrothermal processes, are gaining attention due to their lower environmental footprint compared to traditional methods, such as high-temperature solid-state reactions, which can consume large amounts of energy and result in hazardous byproducts.

1) Sol-Gel Process: The sol-gel process is widely used for synthesizing perovskite-based multiferroic materials due to its flexibility and low-temperature requirements [87]. It significantly reduces energy consumption compared to solid-state methods that require temperatures of 800-1000°C [88].
2) Hydrothermal Synthesis: Hydrothermal synthesis involves high temperature and pressure, but it can operate at much lower temperatures than traditional methods [89]. This method offers energy efficiency, reduced toxic byproducts, and scalability [90].

B. *Reducing Environmental Impact Through the Use of Abundant and Non-Toxic Elements*

Traditional perovskite materials, especially those used in electronics, often rely on toxic elements such as lead (Pb), cadmium (Cd), or thallium (Tl), which pose significant environmental and health risks [91]. The shift to using non-toxic and earth-abundant elements like bismuth (Bi), tin (Sn), zinc (Zn), and magnesium (Mg) can help mitigate these concerns [92].

1) Bismuth (Bi)--based Perovskites: Bismuth is a promising alternative to lead in perovskite materials due to its non-toxicity and environmental sustainability [93].
2) Tin (Sn)-based Perovskites: Tin-based perovskites, such as $CsSnI_3$, exhibit similar properties to lead-based materials but are less toxic and more abundant [94].

C. *Recycling Strategies for Rare-Earth and Other Critical Materials*

Recycling rare-earth elements and other critical materials is essential for reducing the environmental impact of mining and conserving valuable resources [95]. Strategies such as mechanical recycling, hydrometallurgical processes, and urban mining are gaining attention as more sustainable alternatives to traditional mining [96].

1) Hydrometallurgical Processes: Selective leaching methods, such as using organic acids for rare-earth recovery, have been developed to improve extraction efficiency and reduce environmental damage [97].
2) Biotechnological Methods: Biotechnological recycling methods, such as microbial leaching, provide a greener and more energy-efficient alternative to traditional methods [98].

VI. CHALLENGES AND SOLUTIONS

A. *Key Challenges: Scalability, Thermal Stability, and Environmental Considerations*

1) Scalability: The challenge of scaling perovskite multiferroic materials for large-scale applications involves issues like high manufacturing costs, material uniformity, and the complexity of processing [99,100]. Current fabrication techniques such as chemical vapor deposition (CVD) and sputtering are expensive, limiting large-scale production [101]. Low-cost fabrication techniques, such as inkjet printing and roll-to-roll processing, are promising solutions.
2) Thermal Stability: Thermal degradation is a key concern for perovskite materials, as elevated temperatures can cause loss of ferroelectric and magnetic properties. Doping perovskites with rare-earth elements or developing lead-free alternatives, like bismuth-based perovskites, are solutions to enhance thermal stability [102].
3) Environmental Considerations: The toxicity of lead-based perovskites is a significant environmental challenge. Lead and cadmium contamination during the manufacturing and disposal phases are risks [103]. Lead-free alternatives, such as tin-based perovskites and bismuth ferrite, are being researched as environmentally friendly solutions [104].

B. *Potential Solutions: Advanced Material Engineering, Hybrid Device Architectures, and Low- Energy Manufacturing Processes*

1) Advanced Material Engineering
   i. Lead-Free and Low-Toxicity Alternatives: Bismuth-based perovskites and tin-based perovskites are gaining attention for their low toxicity and comparable functional properties to lead-based counterparts [18]. Research into stable high-performance alternatives is critical to mitigating environmental concerns [105].

ii. Doping and Alloying: Doping with transition metals like cerium and neodymium has been shown to enhance the magnetic and ferroelectric properties of perovskites [106]. Strain engineering can also improve multiferroic coupling by applying mechanical stress to the crystal lattice [107].

C. Hybrid Device Architectures

i. Integration with 2D Materials: The integration of perovskite multiferroics with 2D materials, such as graphene and TMDs, can create hybrid devices with enhanced charge transport and stability [108]. This approach can lead to better energy storage and device flexibility [109].
ii. Integration with Organic Materials: Combining perovskites with organic semiconductors can reduce manufacturing costs while maintaining high device performance. Hybrid organic-inorganic devices are particularly beneficial for flexible electronics [110].

D. Low-Energy Manufacturing Processes

i. Solution-Based Synthesis: Techniques like sol-gel processes and inkjet printing are more energy-efficient and scalable compared to high-temperature deposition methods [111]. These approaches also enable the integration of perovskites into flexible substrates.
ii. Roll-to-Roll Manufacturing: This process allows for the continuous production of large-area perovskite films, reducing energy consumption and costs [112]. It is particularly beneficial for the mass production of flexible electronic devices.

VII. CASE STUDIES AND RECENT ADVANCES

A. Examples of Successful Applications Using Multiferroic Perovskites in Memory and Computing

In recent years, multiferroic perovskites have demonstrated remarkable potential for use in memory and neuromorphic computing devices due to their unique properties, including ferroelectricity, magnetism, and magnetoelectric coupling. Several case studies highlight the applicability of these materials in practical systems.

1. Perovskite-Based Memristive Memory Devices:

Case Study: $BiFeO_3$-Based Memristor for Non-Volatile Memory:

A study demonstrated the successful application of bismuth ferrite ($BiFeO_3$) in memristive devices, showcasing its potential for non-volatile memory storage [113]. The $BiFeO_3$-based memristor exhibited excellent multilevel resistance states, low-power operation, and fast switching times, making it an ideal candidate for future memory systems.

Achievements:

i. The $BiFeO_3$-based memristor demonstrated multilevel resistance states and non-volatile data storage [113].
ii. The device exhibited excellent retention times and low energy consumption [113].

Case Study: Lead-Free Perovskite Memristors with Multilevel Resistive States:

Another study, investigated bismuth titanate ($BiTiO_3$) for memristive applications, with a focus on multilevel resistance states [114]. The $BiTiO_3$-based memristors demonstrated low switching voltages, high retention, and enhanced data storage density, offering a promising alternative to traditional binary memory systems.

Achievements:

i. Enhanced data storage density due to multilevel resistance states [114].
ii. Low switching voltages and good retention [114].

2. Neuromorphic Computing: Perovskites for Artificial Synapses:

Case Study: $BiFeO_3$ for Artificial Synapses in Neuromorphic Systems:

A study explored the application of $BiFeO_3$ in artificial synapses for neuromorphic computing, demonstrating the material's ability to replicate the plasticity and learning behaviour of biological synapses [115]. The magnetoelectric coupling in $BiFeO_3$ enabled energy-efficient operation, which is crucial for neuromorphic systems designed for cognitive tasks.

Achievements:

i. Long-term potentiation (LTP) and long-term depression (LTD) were replicated, demonstrating synaptic learning behaviour [115].
ii. Energy-efficient operation with analogue switching, ideal for neuromorphic systems [115].

Case Study: Hybrid Neuromorphic Device Using Perovskite and 2D Materials:

Recent research demonstrated the use of perovskite-2D material hybrid devices for neuromorphic systems, where perovskites were combined with graphene for enhanced switching properties [116]. The hybrid system showed promising results in artificial neural networks and cognitive computing, offering flexible and energy-efficient neuromorphic solutions.

Achievements:

i. The hybrid devices exhibited low-power operation and enhanced switching characteristics for artificial neurons [116].
ii. Flexibility and scalability were demonstrated for wearable electronics and smart sensors [116].

3. Other Applications in Computing and Sensors:

Case Study: Spintronic Devices Using Perovskite:

In exploring the use of perovskite multiferroics in spintronic devices, found that $BiFeO_3$ and other perovskites demonstrated enhanced magnetic switching, showing promise for quantum computing and magnetic sensors [117].

Achievements:

i. Enhanced magnetic switching and data storage capabilities in perovskite-based spintronic devices [117].
ii. Potential use in quantum computing and sensors [117].

B. Notable Research on $BiFeO_3$-Based Devices and Rare-Earth-Free Alternatives

1. $BiFeO_3$-Based Devices:

$BiFeO_3$ continues to be widely studied for its unique ferroelectric and magnetic properties, making it an excellent candidate for memory, neuromorphic computing, and sensor applications [118]. The research explored $BiFeO_3$ in memristive devices, where it exhibited multilevel resistance states essential for high-density memory storage.

Achievements:

i. Strong ferroelectric and magnetoelectric properties in $BiFeO_3$ [118].
ii. $BiFeO_3$ demonstrated efficient memristive behaviour with low power consumption [118].

2. Rare-Earth-Free Alternatives to $BiFeO_3$:

The search for rare-earth-free alternatives has led to promising materials such as bismuth titanate ($BiTiO_3$) and strontium bismuth tantalate ($SrBi_2Ta_2O_9$), which exhibit similar magnetoelectric coupling but without the environmental concerns of rare-earth elements [119]. demonstrated that $BiTiO_3$-based devices are suitable for low-power, high-density memory storage [119].

Achievements:

i. $BiTiO_3$-based devices demonstrated excellent multilevel resistance states for memory applications [119].
ii. Strontium bismuth tantalate exhibited both ferroelectricity and magnetism, making it a viable candidate for non-volatile memory [119].

C. Theoretical Studies on Perovskite Multiferroics

First-principles calculations have been pivotal in understanding the electronic, magnetic, and ferroelectric properties of perovskites. density functional theory (DFT) to model the magnetoelectric coupling in $BiFeO_3$, revealing the impact of strain and doping on device performance [120].

Achievements:

i. DFT calculations showed that strain engineering could enhance the magnetoelectric coupling in $BiFeO_3$-based devices [120].
ii. Computational models predicted the behaviour of rare-earth-free alternatives, guiding the design of sustainable materials for next-generation memory devices [120].

VIII. FUTURE DIRECTIONS

A. Trends in Material Development and Device Integration

The development of new materials for multiferroic devices is a focal point in current research. Significant trends include:

1) New Multiferroic Materials: Materials exhibiting strong magnetoelectric coupling at room temperature are highly sought after. Research into materials such as $BiFeO_3$, rare-earth orthoferrites, and thin-film composites continues to expand, offering the potential for enhanced performance [121].

2) Heterostructures and Hybrid Materials: The integration of multiferroic materials with superconductors, piezoelectrics, and topological insulators in heterostructures allows for superior control and optimization of their properties. This leads to the development of efficient sensors, memory devices, and actuators [122,123].
3) Flexible and Transparent Materials: Innovations in flexible and transparent multiferroic materials broaden the application scope, particularly in wearable electronics, displays, and integrated systems [122,124].
4) Integration into Existing Electronics: Effective integration of multiferroic materials into CMOS-based electronics requires addressing compatibility and scalability challenges. Techniques such as microfabrication, 3D printing, and hybrid integration are actively being researched to streamline this integration [125].

B. Role of AI and Machine Learning in Optimizing Multiferroic Performance

AI and machine learning are playing increasingly crucial roles in optimizing the performance of multiferroic materials and devices:

1) Material Discovery: AI algorithms are accelerating the discovery of new multiferroic materials by predicting their properties, thus reducing the need for extensive experimental trials [126].
2) Optimization of Device Design: ML models are employed to simulate and optimize device designs for energy harvesters, sensors, and actuators, identifying the optimal material combinations and configurations for specific applications.
3) Property Prediction: ML is also being used to predict magnetic and electric polarization responses under various conditions, enabling precise control of multiferroic behaviour [127].
4) Process Optimization: Reinforcement learning and other AI techniques are being applied to optimize processing conditions for multiferroic materials, improving performance and yield.

C. Long-Term Outlook for Sustainable Electronics Powered by Multiferroic Materials

The long-term potential of multiferroic materials in sustainable electronics is promising:

1) Energy Harvesting and Sustainability: Multiferroic materials can drive low-power, energy-efficient devices capable of harvesting ambient energy from vibrations or electromagnetic radiation, making them ideal for sustainable electronics [128,129].
2) Integration in Smart Grids and IoT: Sensors and energy harvesting systems based on multiferroics will be crucial in developing smart grids and IoT devices that are self-powered and do not require external batteries [130,131].
3) Environmental Impact and Green Electronics: The use of eco-friendly materials and low-energy consumption in multiferroic devices aligns with the trend toward environmentally sustainable electronics [124].
4) Long-Term Challenges: Despite their potential, challenges such as scalability, cost, and long-term stability remain. Addressing these will be key for commercial success in multiferroic-based electronics [122].

IX. CONCLUSION

This study explores the emerging role of multiferroic materials, particularly perovskite-based multiferroics, in revolutionizing modern electronics. Key points discussed include:

1) Material Properties and Mechanisms: Multiferroic materials, particularly those with perovskite structures, exhibit unique properties, such as simultaneous magnetization and polarization, which make them ideal for advanced applications in memory storage, sensors, and energy harvesting.
2) Integration and Device Applications: The potential of perovskite multiferroics in memory devices and neuromorphic computing was highlighted, where their ability to manipulate both magnetic and electric states allows for efficient data processing, memory retention, and intelligent computing paradigms.
3) Role of AI and Machine Learning: AI and machine learning are crucial in accelerating the discovery, optimization, and design of multiferroic materials, contributing to the performance enhancement of devices and reducing the time required for material development.
4) Sustainability Focus: The development of sustainable electronics powered by multiferroic materials is becoming more critical, with a focus on energy-efficient devices, renewable energy harvesting, and reducing the environmental footprint of electronics manufacturing.

A. Reiteration of the Potential of Perovskite Multiferroic Materials to Revolutionize Memory and Neuromorphic Computing

Perovskite multiferroic materials hold immense potential to reshape the fields of memory and neuromorphic computing. Their unique ability to exhibit both ferroelectric and ferromagnetic properties simultaneously offers numerous advantages, such as:

1) Improved Memory Devices: The multiferroic properties enable fast, non-volatile memory storage with low energy consumption, which is essential for the future of high-performance computing.
2) Neuromorphic Computing: Perovskite multiferroics can emulate biological processes, enabling the development of neuromorphic systems that mimic the functioning of the human brain. This could lead to breakthroughs in artificial intelligence, particularly in the creation of efficient, energy-conscious neural networks.
3) Energy Efficiency and Speed: Their use in next-generation devices can offer faster data processing speeds with minimal power requirements, making them ideal for both large-scale and portable computing applications.

B. Emphasis on the Importance of Sustainability in Driving Innovation in Electronics

As the electronics industry moves toward more sustainable solutions, multiferroic materials, particularly perovskites, are poised to play a pivotal role. The development of energy-efficient devices that are capable of self-powering through energy harvesting or minimizing power consumption is critical for the future of electronics. Sustainability is not only a matter of reducing environmental impact but also of driving innovation in how we think about and design future electronic systems. As the demand for green technologies increases, multiferroic materials offer a promising solution for developing electronics that align with global sustainability goals. Furthermore, the push for eco-friendly materials and manufacturing processes will likely spur advancements in material science and device integration, paving the way for a more sustainable and efficient electronics industry.

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