BISMUTH FERRITE BASED APPLICATIONS

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Abstract

With the increase in the need for higher data storage density, the recent focus in semiconductor research includes the fabrication of efficient non-volatile memory (NVM) devices. NVM are the storage devices that can retrieve the information even when external power is halted. Resistive random-access memory (ReRAM), which is category of NVM has promising futuristic applications due to its significant characteristics such as low power consumption and fast read/write processing and simplicity in device structure. Bismuth ferrite (BFO) was the most studied material which were deposited using sol gel method, spray pyrolysis technique and Hydrothermal/Solvothermal Synthesis at 576K. The structural analysis of the prepared BFO thin films shows rhombohedral perovskite structure with R3c space group. Bismuth Ferrite stands as an intriguing multiferroic material with exciting potential in various technological applications. Its combination of ferroelectricity and antiferromagnetism offers unique possibilities for developing multifunctional devices with electric and magnetic control. As researchers continue to explore its properties and overcome challenges, Bismuth Ferrite is poised to play a significant role in advancing modern electronics, energy harvesting systems, and information storage technologies.

Introduction

Multiferroic materials have emerged as a fascinating area of research due to their ability to possess multiple properties such as ferro-electricity, ferro-magnetism, and ferro-elasticity in a single crystal [1]. This coexistence of different order parameters within a crystalline phase opens up new avenues for advanced technologies and, scientific exploration in multiferroic based bismuth ferrite (BFO) for various applications [2-4]. BFO possesses a distorted rhombohedral structure, belonging to the R3c space group, and exhibits an energy bandgap (E_g) of 2.8 eV , high dielectric constant (k = 6) and a large remanent polarization [7]. These unique properties make BFO highly versatile and offer numerous applications in memory devices, sensors, spintronics, data storage, and telecommunications [8]. Over the years, various forms of bismuth ferrite (BFO)-based nanomaterials have been developed, including ceramics, thin films, and nanostructures [8]. For instance, BFO ceramics have demonstrated a high value of the piezoelectric coefficient (d33) and excellent thermal stability, attributed to the reduction of leakage current [9]. Wang et al (2003). reported the first BFO thin film with a remnant ferroelectric polarization (Pr~55 μC cm^{-2}), surpassing previous reports on single crystal samples [5]. The ferroelectric characteristics of BFO stem from the presence of Bi^{3+} ions, while the ferromagnetic properties arise from Fe^{3+} ions [6]. Kethirvel et al reported the BFO paste heterojunction response photo light, photo detector. He also reported high responsibility ~65 μA/w with intensity 100 mw/cm^2 and photo current 5.6 nA. Kossar at el focuses on fabricating UV photodetectors using Bismuth Ferrite (BiFeO3) thin films with varying thicknesses by using Spray pyrolysis was to deposit BFO thin films on glass substrates. Characterization revealed uniform grain distribution, and optical analysis indicated an optimum thickness (365 nm) for higher photoresponsivity (110 mA/W) and external quantum efficiency (EQE) of 37.30%. Oxygen (O2) adsorption and desorption on the BFO surface played a vital role in the UV photo response characteristics [70]. Lee at el study utilized rf-magnetron sputtering to fabricate pure perovskite BFO films at low temperatures and also investigated the effects of La doping on crystal structure, surface topography, leakage, dielectric properties, polarization switching, ferroelectric reliability, and magnetic behavior [71]. X. Deng et al reported on Ni-doped BFO thin films were fabricated via sol-gel method on FTO/glass substrate. In which Ni doping induced a structure transition, increased oxygen vacancies, and impacted grain growth. Enhanced ferroelectric, piezoelectric, and magnetic properties were observed with Ni doping x=0.10, while optical band gap decreased to 2.46 eV [72].

In recent years, researchers have been attracted by BFO-based nanomaterials due to their extraordinary multifunctional properties. These materials hold great potential for revolutionizing various technological fields, ranging from electronics to energy storage and beyond [10]. The ability to manipulate and control different order parameters within a single crystal offers exciting opportunities for developing novel devices and systems with enhanced performance and functionality [10].

This book chapter aims to provide a comprehensive overview of bismuth Ferrite (BFO) and its nanomaterial counterparts, focusing on their synthesis, structural properties, and multifunctional characteristics. We will explore the challenges encountered during the fabrication of pure BFO and delve into the innovative techniques employed to overcome these obstacles. Furthermore, the chapter will delve into the various applications of BFO-based nanomaterials and discuss their potential implications in diverse fields. By delving into the cutting-edge research and discoveries surrounding Bismuth Ferrite, this chapter aims to shed light on the immense potential and future directions in this rapidly evolving field.

Synthesis of Bismuth ferrite-based Nanomaterial

There are several methods for preparing bismuth ferrite-based nanomaterials, each with its own advantages and limitations. Here are some commonly used techniques:

1. **Sol-Gel Method**: This method involves the hydrolysis and condensation of metal alkoxides or metal salts in a solution to form a gel. The gel is then heat-treated to obtain the desired

nanomaterial. The sol-gel method allows control over composition and particle size, and it is relatively simple and versatile [11].

The Sol-Gel method for synthesizing bismuth ferrite-based nanomaterials typically involves the following steps and equipment:

a) **Precursor Solution Preparation**: Prepare precursor solutions by dissolving appropriate bismuth and iron precursors (such as metal alkoxides or salts) in a suitable solvent. The choice of precursors and solvent depends on the desired synthesis conditions and the specific Sol-Gel variant being used.

b) **Mixing and Homogenization**: Combine the bismuth and iron precursor solutions while stirring to ensure a homogeneous mixture. Magnetic stirrers or overhead stirrers can be used for this purpose.

c) **Hydrolysis and Gel Formation**: Add a hydrolyzing agent, such as water or an alcohol, to initiate the hydrolysis reaction. This results in the formation of a gel, where the metal ions start to form a network within the solvent. The gelation process can be accelerated by adjusting the pH and temperature.

d) **Aging and Maturation**: Allow the gel to age and mature at a controlled temperature for a specific duration. This step promotes the growth and structural development of the gel network, leading to improved properties in the final nanomaterials.

e) **Drying**: Remove the solvent from the gel by drying. This can be done through various methods, such as evaporation, freeze-drying, or supercritical fluid extraction. The choice of drying method depends on the specific requirements and characteristics of the nanomaterials.

f) **Calcination**: Heat the dried gel at elevated temperatures to induce a solid-state reaction and crystallize the bismuth ferrite phase. The calcination process removes any remaining organic components and further enhances the crystallinity and purity of the nanomaterials.

g) **Cooling and Collecting**: Allow the sample to cool down to room temperature. Collect the resulting bismuth ferrite nanomaterials, which are typically in the form of powders or gels.

Throughout the process, it is essential to maintain controlled conditions, such as temperature, pH, and stirring, to ensure reproducibility and obtain desired nanomaterial properties.

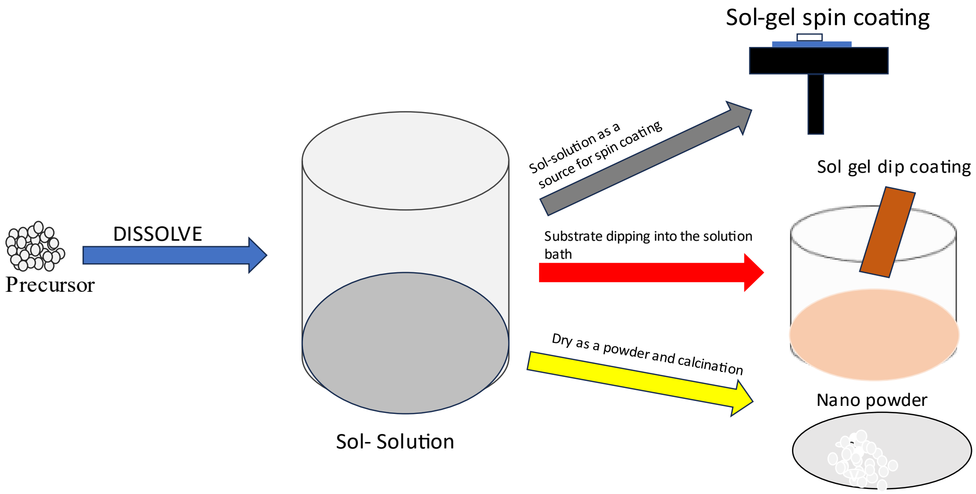


Figure 1: The Synthesis of Bismuth ferrite-based Nanomaterial by Sol gel Technique [11].

2. Hydrothermal/Solvothermal Synthesis:

Hydrothermal or solvothermal synthesis is a widely used method for preparing bismuth ferrite (BFO) nanomaterials. This technique involves the reaction of precursor solutions in a closed vessel under high-pressure and elevated temperature conditions [12]. Here's a detailed description of the hydrothermal/solvothermal synthesis process for BFO:

a) **Precursor Solution Preparation**: Prepare separate precursor solutions for bismuth and iron sources. Typically, bismuth nitrate (Bi(NO3)3) and iron nitrate (Fe(NO3)3) are used as the precursor salts. Dissolve the appropriate amounts of these salts in a solvent, such as distilled water or an organic solvent like ethanol, to obtain the precursor solutions.

b) **Mixing and Homogenization**: Combine the bismuth and iron precursor solutions in a suitable container while stirring to ensure a homogeneous mixture. Magnetic stirrers or ultrasonic agitation can be used for effective mixing.

c) **Transfer to Reaction Vessel**: Transfer the mixed precursor solution to a sealed reaction vessel that can withstand high-pressure conditions. The vessel is typically made of stainless steel or Teflon-lined autoclaves.

d) **Sealing the Vessel**: Ensure that the reaction vessel is tightly sealed to maintain the high-pressure conditions during the synthesis process.

e) **Hydrothermal/Solvothermal Reaction**: Place the sealed reaction vessel in an oven or furnace and heat it to the desired reaction temperature, typically ranging from 100°C to 200°C. The reaction time can vary from a few hours to several days, depending on the desired properties and the specific synthesis conditions.

f) **Cooling and Retrieval**: After the completion of the reaction, allow the reaction vessel to cool down naturally to room temperature. Carefully retrieve the resulting precipitate or solution from the vessel.

g) **Washing and Filtration**: Wash the obtained precipitate or solution with a suitable solvent, such as distilled water or ethanol, to remove any residual impurities or unreacted precursor salts. Filtration can be employed to separate the solid precipitate from the liquid solution.

h) **Drying and Calcination (Optional):** Dry the washed precipitate in an oven or at a controlled temperature to remove the solvent completely. Optionally, perform a calcination step by heating the dried material at elevated temperatures (typically around 600°C to 800°C) to enhance the crystallinity and purity of the BFO nanomaterials.

It is important to note that the specific synthesis parameters, such as reaction temperature, time, and precursor concentrations, may need to be optimized based on the desired properties and the specific hydrothermal/solvothermal setup being used [12]. Additionally, safety precautions, such as wearing appropriate protective gear and handling high-pressure vessels carefully, should be followed throughout the process.

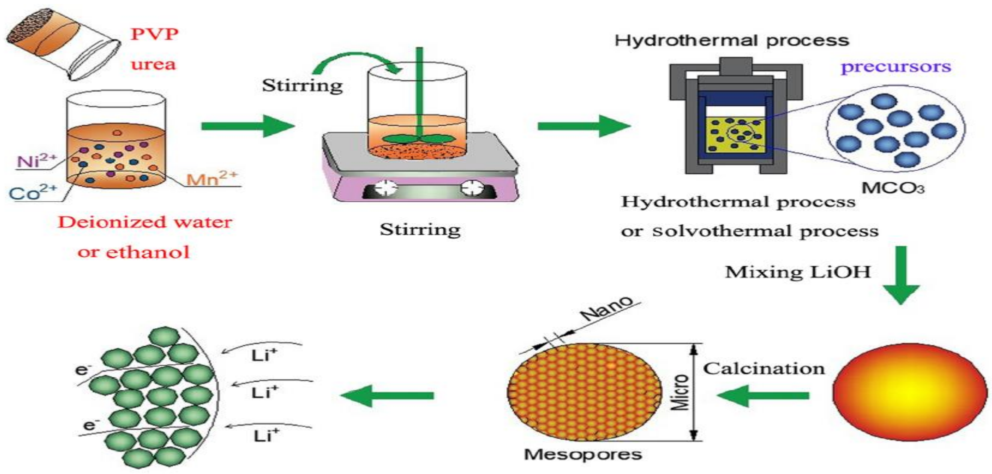


Figure 2: The synthesis of Bismuth ferrite-based by hydrothermal/Solvothermal [12].

3. **Spray pyrolysis**: The spray pyrolysis method is a commonly used technique for synthesizing bismuth ferrite (BFO) nanomaterials. It involves the atomization of precursor solutions into fine droplets, which are then pyrolyzed at high temperatures to obtain BFO nanoparticles [13]. Here's a step-by-step description of the spray pyrolysis method for BFO synthesis:

   a) **Precursor Solution Preparation**: Prepare precursor solutions for bismuth and iron sources separately. Commonly used precursor salts include bismuth nitrate (Bi(NO3)3) and iron nitrate (Fe(NO3)3). Dissolve the appropriate amounts of these salts in a suitable solvent, such as distilled water or ethanol, to obtain the precursor solutions.

   b) **Atomization**: Atomize the precursor solutions into fine droplets. This can be achieved using a nebulizer, ultrasonic nozzle, or other atomization techniques. The aim is to create a fine mist of droplets for efficient pyrolysis.

c) **Pyrolysis Chamber Setup**: Set up a pyrolysis chamber equipped with a heating system. The chamber should be capable of withstanding high temperatures and have a controlled atmosphere if necessary (e.g., inert gas).

d) **Droplet Deposition**: Direct the atomized droplets into the pyrolysis chamber, allowing them to deposit onto a suitable substrate. The substrate can be a glass slide, silicon wafer, or any other material compatible with the pyrolysis process.

e) **Pyrolysis**: Heat the substrate and the deposited droplets in the pyrolysis chamber at high temperatures, typically ranging from 400°C to 800°C. The pyrolysis process decomposes the precursor molecules, leading to the formation of BFO nanoparticles on the substrate.

f) **Cooling**: After the pyrolysis process, allow the substrate and the synthesized BFO nanoparticles to cool down to room temperature.

g) **Collection and Washing**: Carefully collect the substrate with the synthesized BFO nanoparticles. Wash the substrate with a suitable solvent, such as distilled water or ethanol, to remove any residual impurities or unreacted precursor salts.

h) **Drying**: Dry the washed substrate and BFO nanoparticles, either by air drying or using an oven or furnace at a controlled temperature. Ensure complete removal of the solvent.

i) **Substrate Separation (Optional)**: If the BFO nanoparticles are required as a powder rather than on a substrate, separate them from the substrate using techniques like scraping, sonication, or dissolution, depending on the substrate type and adhesion.

It's important to note that the specific parameters, such as precursor concentration, pyrolysis temperature, deposition time, and substrate choice, may need to be optimized based on the desired properties and the specific spray pyrolysis setup being used. Additionally, follow appropriate safety measures, such as using protective gear and handling high temperatures with caution.

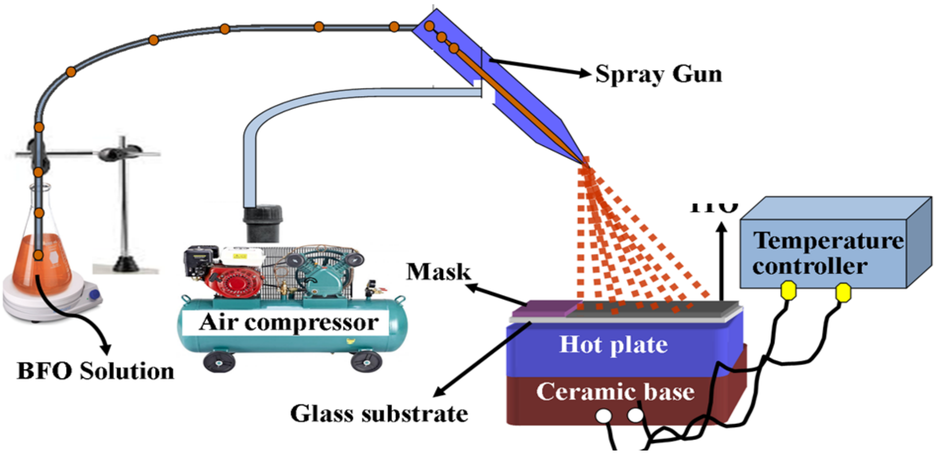


Figure 3: The Synthesis of Bismuth ferrite-based Nanomaterial by Spray pyrolysis [13,70].

Applications of BFO:

Bismuth ferrite (BiFeO3 or BFO) is a multiferroic material that has attracted significant attention in the research community due to its unique combination of ferroelectric and antiferromagnetic properties [14]. This distinctive behavior makes it promising for various applications in the fields of electronics, spintronics, and nanotechnology [15]. In this book chapter, we will explore the diverse applications of Bismuth ferrite:

1. **Photovoltaics**:

The Ferroelectric-Photovoltaic (FPV) effect presents an exciting avenue for efficient light-to-electricity conversion in ferroelectric materials upon exposure to light [16]. However, conventional materials like $LiNbO_3$ face limitations due to their large bandgap and low conductivity, resulting in limited photocurrent generation [17]. Bismuth ferrite (BFO) emerges as a promising candidate for FPV applications as it exhibits a notable photocurrent effect and generates an above-bandgap voltage under illumination [18].

Although BFO shows significant potential, most research has been centred on its thin film form. To further improve its photovoltaic properties, researchers have explored bilayer structures by incorporating BFO with polymers, graphene, and semiconductors [19]. One such approach involved the investigation of a p-i-n heterojunction comprising BFO nanoparticles and oxide-based carrier transporting layers [20].

Despite these advancements, the power conversion efficiency achieved with BFO-based photovoltaic devices still lags behind expectations. Consequently, addressing this challenge becomes crucial to fully unleash the potential of BFO as a high-performance photovoltaic material [21].

Efforts to optimize the power conversion efficiency involve exploring novel techniques, advanced materials engineering, and interface control [22]. By precisely tuning the heterojunction interfaces and understanding charge carrier dynamics in BFO, researchers aim to enhance charge separation, transport, and collection processes [23].

In conclusion, the Ferroelectric-Photovoltaic effect shows great promise in revolutionizing photovoltaic technologies [17]. While conventional materials like $LiNbO_3$ have limitations, Bismuth ferrite emerges as an attractive alternative with its remarkable photocurrent effect and above-bandgap voltage generation [7]. Incorporating BFO into bilayer structures opens up new possibilities for enhancing its photovoltaic performance [24].

Nevertheless, to fully harness the potential of BFO-based photovoltaic devices, researchers need to address the challenge of improving power conversion efficiency. This requires continued exploration of innovative strategies, materials, and interface engineering techniques to unlock the full potential of BFO as a high-performance photovoltaic material for sustainable energy applications.

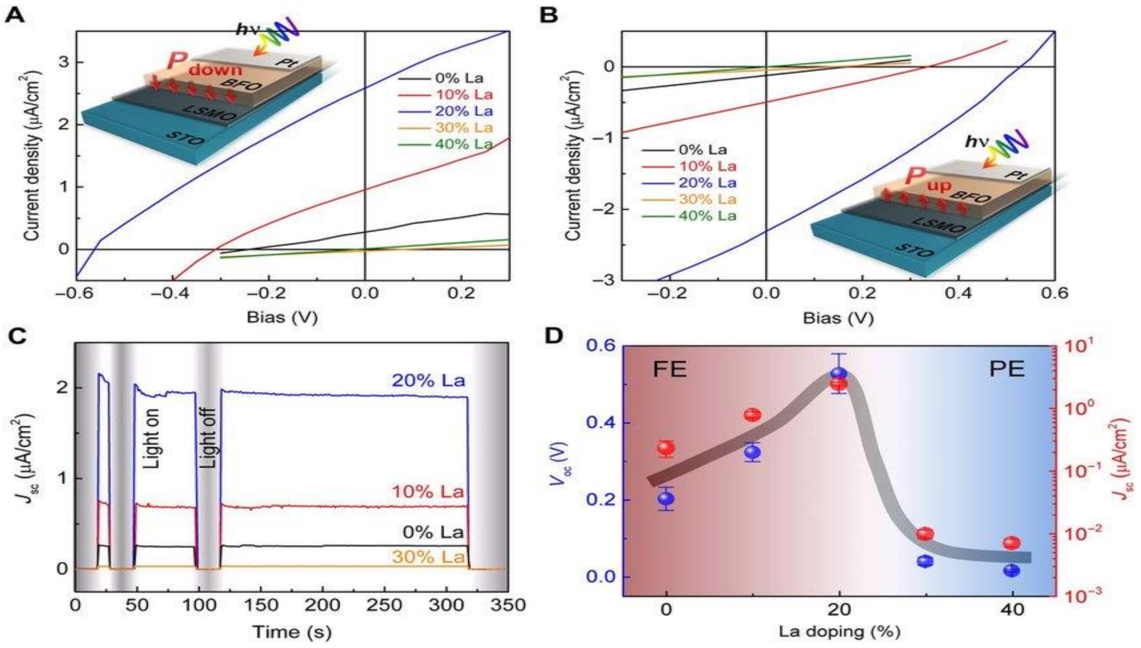


Figure 3: Application of Bismuth ferrite-based Nanomaterial in the field of Photovoltaics [24].

2. **Spintronics**:

Bismuth ferrite (BFO) has gained significant interest in spintronics due to its multifunctional properties, such as ferroelectricity, magnetism, and strong spin-orbit coupling [25]. Its potential applications in spintronics are promising and have been extensively explored [26]. This article provides a comprehensive overview of BFO's applications in spintronics, highlighting its unique features and challenges.

One of the key applications of BFO in spintronics is spin manipulation and control. The strong spin-orbit coupling in BFO enables efficient conversion between charge and spin currents. Spin current can be generated by photoexcitation or electrical means, leading to spin accumulation at interfaces or domain walls [27]. The control of spin currents in BFO can be achieved through electric field or strain, exploiting its ferroelectric and piezoelectric properties [27]. This ability to manipulate spins makes BFO a potential candidate for spin-based devices, such as spin transistors and spin valves [28].

Another exciting application is the use of BFO as a spin filter or spin polarizer. Due to its unique band structure and spin-orbit coupling, BFO can selectively transmit or block spins with specific orientations [29]. By integrating BFO into spintronic devices, it becomes possible to control the spin polarization and manipulate the spin transport, allowing for efficient spin manipulation and information processing [27].

Moreover, BFO's magnetoelectric coupling provides opportunities for spintronic memory and logic devices [30]. The coupling between its ferroelectric and magnetic order parameters allows for electric-field control of magnetism [31]. This feature can be exploited to design energy-efficient magnetoelectric spintronic devices, such as electrically controlled magnetic random-access memory (MRAM) and magnetoelectric logic devices [32]. By combining memory and logic functionalities in a single device, BFO-based spintronics has the potential to revolutionize information processing technologies [33].

Furthermore, BFO's topological properties have attracted attention in spintronics research. It has been theoretically predicted that BFO can host topological insulating phases, where spin-polarized surface states appear in the band gap [7, 27]. These topological surface states may exhibit high spin Hall conductivity, making BFO a promising candidate for spin Hall effect devices and spin-based quantum computing [27].

Despite these promising applications, several challenges need to be addressed to fully exploit BFO's potential in spintronics. One major challenge is to enhance the spin-polarization efficiency in BFO-based devices. The presence of defects, grain boundaries, and surface states can lead to spin scattering, reducing the spin transport efficiency [34]. Strategies such as interface engineering, defect control, and strain engineering are being explored to improve the spin polarization and spin transport properties in BFO [35].

Another challenge lies in achieving efficient spin injection and detection in BFO. Efficient spin injection from a ferromagnetic electrode into BFO and spin detection in BFO are critical for realizing practical spintronics devices [36]. Optimizing the interface properties between BFO and ferromagnetic materials and developing efficient spin detection schemes are crucial for advancing BFO-based spintronics [29].

In conclusion, BFO holds great promise for spintronics applications due to its unique combination of ferroelectric, magnetic, and spin-related properties. Its ability to manipulate spins, act as a spin filter, and provide magnetoelectric coupling opens up exciting possibilities for next-generation spintronic devices. However, further research is needed to overcome existing challenges and unlock the full potential of BFO in spintronics. As the field of spintronics continues to evolve, BFO-based spintronic devices are expected to play a vital role in future information processing and computing technologies.

3. For Electronics

Bismuth ferrite (BFO)-based nanomaterials exhibit both ferroelectricity and ferromagnetism at room temperature, making them promising candidates for high-density ferroelectric devices like nonvolatile memories [37]. However, achieving fast and stable reversibly switchable performance is crucial for practical data storage and logic devices [38]. To address this challenge, researchers have made various attempts to tune the ferroelectric resistive switching in BFO-based nanomaterials.

One study by Wang et al. utilized an atomically tetragonal BFO ultrathin film and observed a stable ferroelectric polarization and switching behavior [39]. The researchers found that even with a thickness of only 2 unit cells, the BFO film displayed strong hysteresis behavior and a butterfly-like shape in the out-of-plane piezoresponse force microscopy (PFM) images, confirming sustained ferroelectricity performance [40]. Additionally, a 1 unit cell-thick BFO film showed a tunneling electroresistance effect of approximately 370% at room temperature in ferroelectric tunnel junctions, indicating excellent performance [41]. These findings were attributed to ionic displacements in the oxide electrode and surface charges, which hold potential for miniaturizing ferroelectric-based nonvolatile memories.

In another study, Lu et al. introduced Ti-doped BFO films and proposed an electric-optical memory prototype [41]. This device allowed writing in an electric state and reading in an optical state. The films exhibited a filament-type resistive switching effect, and the resistance state could control the photovoltaic open-circuit voltage reliably, enabling repeatable manipulation [42]. Doping Ti in the BFO films further enhanced their performance, offering a promising avenue for the development of next-generation memory devices [41].

One family of devices that utilizes BFO's ferroelectric domain walls is the ferroelectric domain wall memories. Ferroelectric domain walls are nanoscale topological defects that can separate spontaneous topological structures and be individually controlled [42]. Researchers have proposed BFO nanostructures, such as high-density and well-ordered BFO nanoislands and nanodots, for use as nonvolatile memory devices. These devices exhibit high OFF-ON ratios, excellent retention, and robust endurance characteristics. For example, a prototype nonvolatile ferroelectric domain wall memory demonstrated nondestructive readout at moderate voltages and high switching stability over thousands of cycles. Overall, these studies demonstrate the potential of BFO-based nanomaterials for high-density and reliable ferroelectric memory applications. By fine-tuning the material properties and leveraging innovative device designs, researchers aim to unlock the full potential of BFO nanomaterials in advancing nonvolatile memory technologies for future data storage and logic devices [44].

In terms of improving the switching speed and endurance of BFO-based nonvolatile memories, various strategies have been explored. While most reported switching speeds are in the microsecond level, achieving the nanosecond level required for universal memory remains a challenge. Further studies are needed to optimize the device structures and material properties to achieve high-speed and reliable switching [45].

Additionally, the photovoltaic effect of BFO has also been utilized in ferroelectric memory applications. Wang et al. demonstrated that the photovoltaic effect of BFO could be used for high-speed writing in ferroelectric memory, indicating its potential for constructing photovoltaic effect-based ferroelectric memory devices [48].

Beyond memory applications, BFO-based nanomaterials have been investigated for energy storage properties. By engineering the microstructure of BFO-based ceramics, researchers achieved high discharge energy densities and efficiencies, making them promising candidates for energy storage nanomaterials with higher energy and power density [47].

Furthermore, BFO-based nanomaterials have been used to induce a two-dimensional electron gas (2DEG) at heterostructure interfaces. By using BFO-TbScO3 heterostructures, Zhang et al. demonstrated an interfacial 2DEG induced by ferroelectric polarization. The conductivity of the 2DEG was anisotropic, depending on the polarization orientation, and this work opens up new possibilities for engineering advanced device applications that can modulate two-dimensional anisotropic electronic transport by tuning the ferroelectric polarization [46].

Moreover, BFO has been investigated for its elastic dynamics during phase transitions. Researchers found that the piezoresponse enhanced near the rhombohedral-tetragonal phase transition, leading to giant electrically tunable elastic stiffness [49]. This property broadens the potential applications of BFO in frequency-agile electroacoustic devices.

In conclusion, BFO-based nanomaterials have shown significant promise in various fields, including nonvolatile memories, energy storage, 2DEG, and electroacoustic devices . The unique combination of ferroelectric and ferromagnetic properties at room temperature makes BFO a versatile material for developing innovative devices with enhanced functionalities and performance. As researchers continue to explore and optimize BFO nanomaterials, they hold great potential to revolutionize various technologies and contribute to the advancement of modern electronics and information storage systems.

4. **Multiferroic Devices**: Bismuth ferrite's multiferroic nature, where it simultaneously exhibits ferroelectric and antiferromagnetic properties, opens up possibilities for the development of novel multiferroic devices. These devices can be designed to be electrically controlled using an external electric field while also responding to magnetic fields. Potential applications include magnetoelectric sensors, actuators, and memory devices [50].
5. **Non-Volatile Memory**: Bismuth ferrite has shown promise as a potential candidate for non-volatile memory applications, such as ferroelectric random-access memory (FeRAM). FeRAM offers advantages over traditional memory technologies like Flash memory in terms of faster read/write speeds, lower power consumption, and higher data retention. Li, Dong, et al. on of his paper on "La-doped BiFeO3 junction based random access multilevel nonvolatile memory." Shows results in which XRD θ–2θ scan of the LBFO/NSTO heterostructure showed only (001) and (002) diffraction peaks of the LBFO film, indicating a single crystal direction. X-ray reflectance measurements confirmed the

LBFO film thickness to be approximately 6.2 nm [51]. The etched NSTO surface exhibited flat atomic-level steps with a separation of ∼4 Å. The LBFO film's surface morphology showed excellent quality with a square root roughness of 0.365 nm.

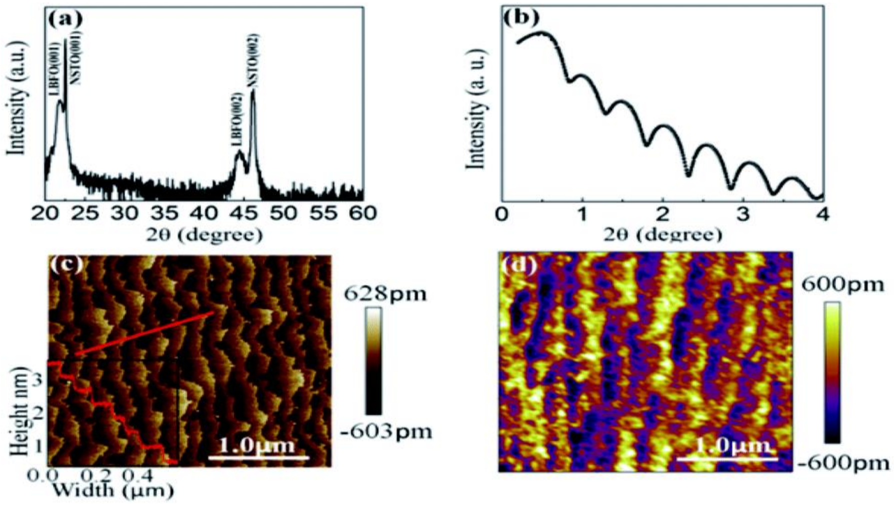


Fig. 1 (a) XRD θ–2θ scan of the LBFO/NSTO (001) heterostructure. (b) X-ray reflectivity (XRR) measurements of the LBFO film. (c) Morphology of the etched NSTO. (d) Surface morphology of the 6.2 nm-thick LBFO layer grown on an NSTO substrate [51].

6. Piezoelectric device

Piezoelectric devices are a type of transducer that can convert mechanical energy into electrical energy and vice versa. They are based on the piezoelectric effect, which is the ability of certain materials to generate an electric charge in response to applied mechanical stress or to deform when subjected to an electric field. This effect was first discovered in 1880 by Pierre and Jacques Curie, and since then, it has found numerous practical applications in various industries [52].

Piezoelectric materials are crystalline substances, such as certain ceramics and crystals quartz, tourmaline, lead zirconate titanate, which exhibit the piezoelectric effect. When these materials experience mechanical stress or pressure, their internal positive and negative charges get displaced, creating an electric potential across the material.

Conversely, when an electric field is applied to the material, it causes a change in its shape or dimensions, leading to mechanical deformation [53].

Common applications of piezoelectric devices

1. Piezoelectric Sensors: These sensors can measure pressure, force, acceleration, and strain. They are used in various industries, including automotive, aerospace, medical, and consumer electronics.
2. Piezoelectric Actuators: These devices use the reverse piezoelectric effect to change their shape when an electric field is applied. They are used for precise positioning, vibration control, and micro/nano-scale movements in applications like scanning probe microscopes, fuel injectors, and precision motors.
3. Piezoelectric Transducers: These are used to convert electrical signals into acoustic waves or vice versa. Piezoelectric transducers are found in ultrasound machines, sonar systems, and speakers.
4. Piezoelectric Igniters: Piezoelectric materials can generate a spark when mechanically stressed, making them suitable for gas lighters and some types of igniters.
5. Piezoelectric Energy Harvesters: These devices are designed to scavenge ambient mechanical energy (e.g., vibrations, footsteps) and convert it into electrical energy. They find applications in powering low-power electronic devices and wireless sensors.
6. Piezoelectric Microphones: They are used in various audio devices to convert sound waves into electrical signals.
7. Piezoelectric Generators: These are used to harvest energy from mechanical sources, such as vibrations in industrial settings or from human movements in wearable devices.

Piezoelectric devices offer several advantages, such as high precision, fast response times, low power consumption, and a wide frequency range.

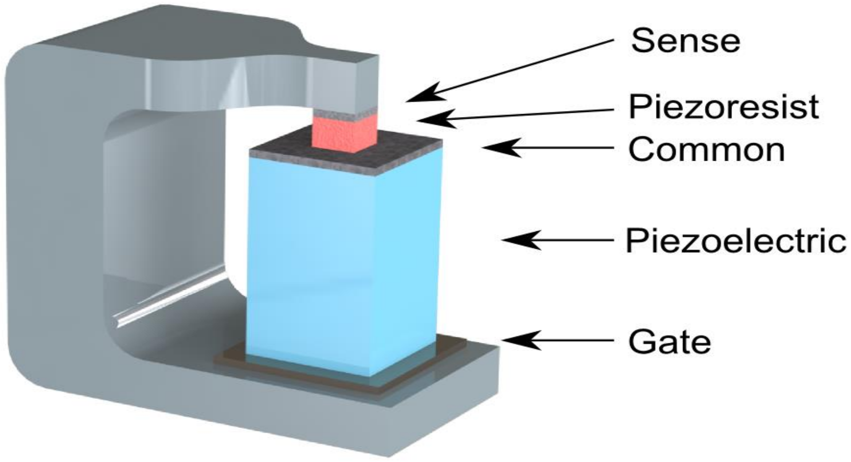


Figure 6: Application of Bismuth ferrite-based Nanomaterial for Piezoelectric device [52-53].

7. Catalysis:

- Catalysis is a process in which a substance, known as a catalyst, facilitates a chemical reaction without itself undergoing any permanent chemical change. Catalysts work by providing an alternative reaction pathway with lower activation energy, enabling the reaction to occur more rapidly or at lower temperatures compared to the uncatalyzed reaction [55].
- The main role of a catalyst is to increase the rate of a chemical reaction by lowering the activation energy barrier. Activation energy is the minimum energy required for reactant molecules to collide with enough force and proper orientation to form the products. By providing an alternative pathway with a lower activation energy, the catalyst allows a larger fraction of the reactant molecules to acquire the necessary energy to react, leading to an overall faster reaction.

- Catalysts are not consumed during the reaction, and they can be recovered unchanged at the end of the process. This means that a small amount of catalyst can be used to accelerate the reaction of a large number of reactants, making catalysis an economically and environmentally favorable strategy for many industrial processes.

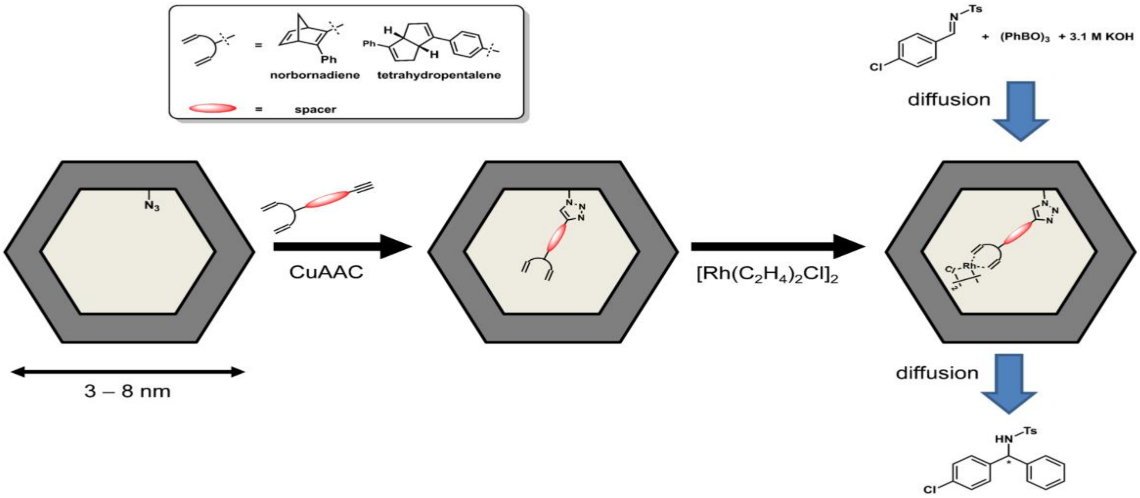


Figure 7: Application of Bismuth ferrite-based Nanomaterial for Catalysis [55].

8. **Electrochemical Devices**:

Electrochemical biosensors are analytical devices that combine the principles of electrochemistry with biological recognition elements to detect and quantify specific biological analytes. These sensors are widely used in various fields, including medical diagnostics, environmental monitoring, food safety, and biotechnology. Electrochemical biosensors offer several advantages, such as high sensitivity, specificity, and rapid response times, making them valuable tools for real-time and point-of-care applications [54].

Components of Electrochemical Biosensors:

1. Biological Recognition Element: This is the part of the biosensor that interacts specifically with the target analyte of interest. The recognition element can be an

enzyme, antibody, nucleic acid, receptor, or whole cell, depending on the type of analyte being detected.

2. Transducer: The transducer converts the biochemical interaction between the recognition element and the analyte into an electrical signal. Common transducers in electrochemical biosensors include amperometry, potentiometric, and impedimetric sensors.
3. Electrode: The electrode is an essential component of the transducer and serves as the interface between the biological recognition element and the electrical circuit. The electrode's surface is usually modified with the recognition element to facilitate the detection of the analyte.

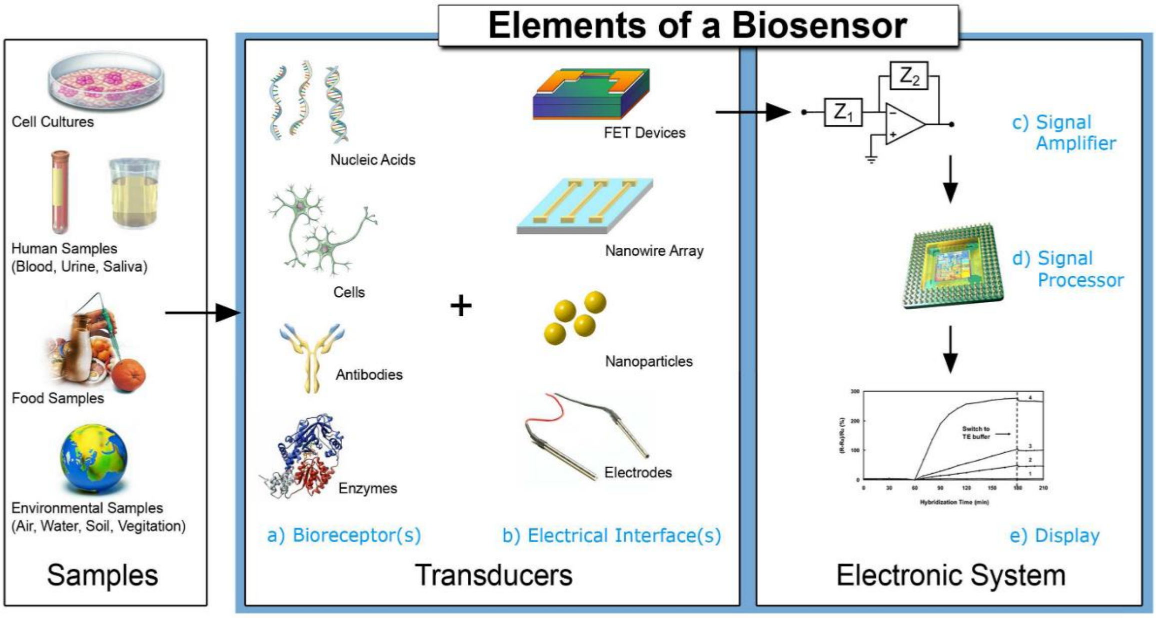


Figure 8: Application of Bismuth ferrite-based Nanomaterial for Electrochemical Devices [54].

9. Biomedical Applications

Biomedical applications encompass a wide range of scientific and technological advancements used in understanding, diagnosing, treating, and preventing diseases to improve human health. These applications integrate biology, medicine, and engineering to develop practical tools and techniques that transform healthcare and are discussed.

1. Medical imaging, gene editing, and gene therapy are key biomedical applications that aid in early disease detection, correct genetic disorders, and provide novel treatment options.
2. Tissue engineering and regenerative medicine focus on creating artificial tissues and organs for transplantation, addressing organ shortages and improving patient outcomes.
3. Biomarker detection enables personalized medicine by using specific molecules as indicators for diagnosing diseases and predicting treatment responses.
4. Nanomedicine employs nanotechnology to deliver drugs precisely to affected areas, reducing side effects and enhancing treatment efficacy.
5. Telemedicine revolutionizes healthcare delivery by offering remote medical consultations and diagnostics, especially for underserved regions.
6. Advancements in cancer therapies, such as targeted therapies and immunotherapies, provide more effective and personalized treatment options for cancer patients.

Ongoing research and interdisciplinary collaboration continue to drive biomedical applications, holding the potential to shape the future of medicine and tackle global health challenges effectively.

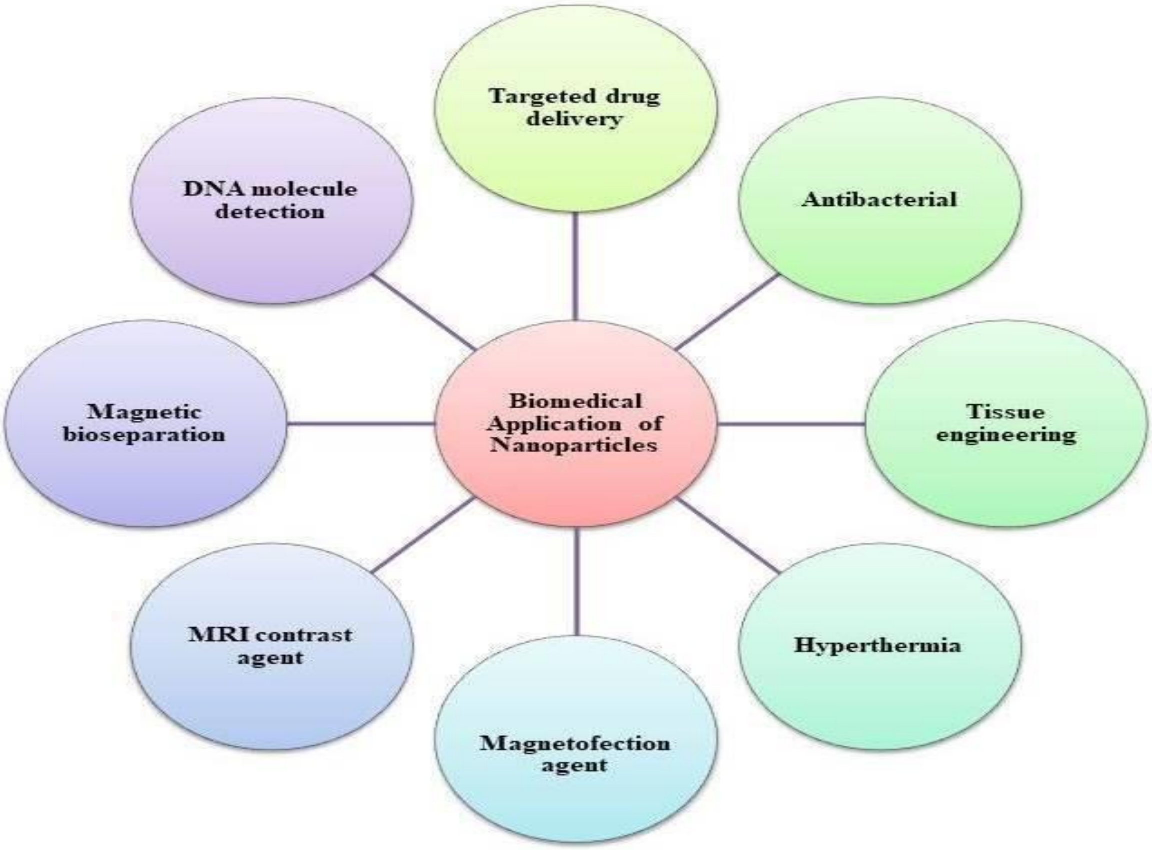


Figure 9: Biomedical Application of Bismuth ferrite-based Nanomaterial.

10. Magnetic sensors

Magnetic sensors are devices that detect and measure magnetic fields. These sensors play a vital role in various applications across multiple industries, utilizing the interaction between magnetic fields and sensor components to provide valuable information about the surrounding environment [67].

The functioning of magnetic sensors is based on the principle of magnetoresistance, where changes in the magnetic field cause variations in the electrical resistance of the sensor material. When exposed to a magnetic field, the sensor's electrical properties change, and these changes can be measured and converted into useful data [68].

There are different types of magnetic sensors, each with its unique characteristics and applications:

1. Magnetic Compasses: One of the earliest uses of magnetic sensors is in compasses. Magnetic compasses utilize a magnetic needle that aligns itself with the Earth's magnetic field, providing orientation and navigation information [69]. They have been essential tools for centuries, guiding travelers, sailors, and explorers.
2. Magnetic Proximity Sensors: These sensors detect the presence or absence of nearby magnetic objects. They are widely used in automation and robotics to sense the position of moving components, identify the opening and closing of doors, and act as safety switches in various industrial applications. They are also employed in security systems to trigger alarms when magnetic contacts are disturbed.
3. Magnetic Resonance Imaging (MRI): In medical applications, magnetic sensors are a core component of Magnetic Resonance Imaging (MRI) machines. MRI utilizes powerful magnets to create detailed images of internal body structures. Magnetic sensors are essential for generating and controlling the magnetic fields required to produce accurate and high-resolution images, aiding in diagnosis and medical research.
4. Magnetic Encoders: Magnetic encoders are used in motor control systems and robotics to measure rotational position, speed, and direction. They employ magnetic fields to detect the movement of a rotating shaft, providing precise feedback for closed-loop control systems. Magnetic encoders are critical in applications where accuracy and reliability are crucial, such as in industrial automation and robotics.
5. Magnetic Stripe Readers: Magnetic stripe readers are widely used in various card-based systems, including credit cards, debit cards, ID cards, and access control cards. The magnetic stripe on these cards contains encoded data, and magnetic stripe readers are

used to read this data and perform specific actions, such as authorizing a transaction or granting access to a restricted area.

Magnetic sensors have become integral components in a wide range of technologies, from consumer electronics and automotive systems to industrial machinery and medical equipment. Their ability to detect and measure magnetic fields accurately and efficiently makes them indispensable for numerous applications, enhancing functionality, precision, and control in diverse devices and systems.

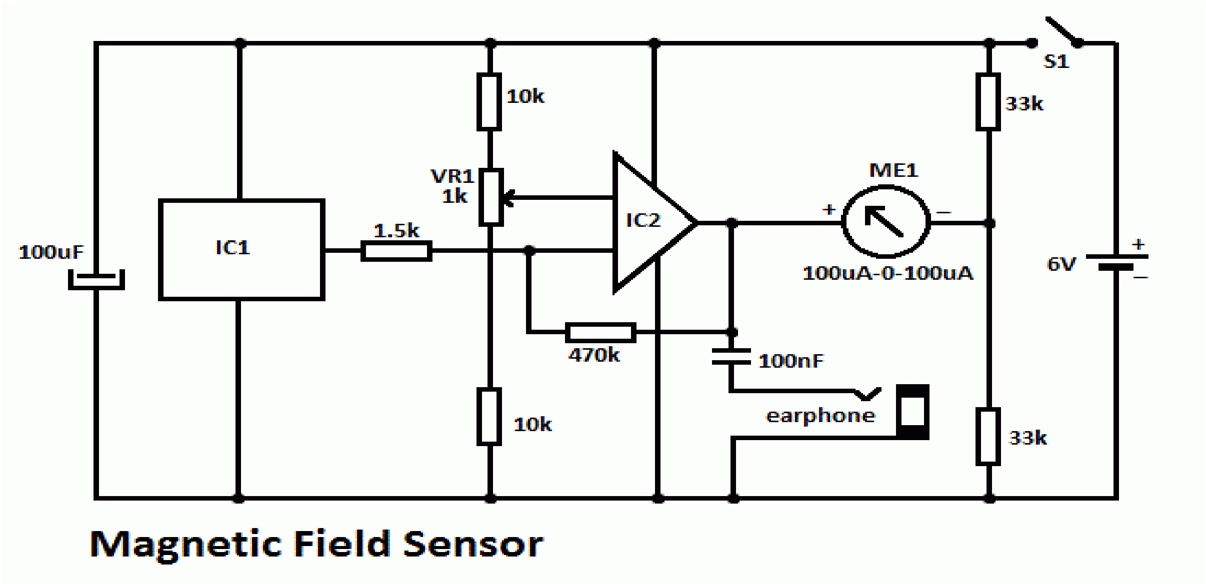


Figure 10: Application of Bismuth ferrite-based Nanomaterial for magnetic field sensor [67-68]

11. **Data storage**

Data storage is the process of storing digital information in a structured and accessible manner for later retrieval and use. In the digital age, data storage is an essential component of various fields, including computing, business, research, healthcare, and entertainment [65]. It involves preserving data in a secure and reliable manner to ensure its integrity and availability when needed.

Data storage technologies have evolved significantly over time, offering diverse solutions to meet various requirements for capacity, speed, reliability, and cost-effectiveness [65]. Some common types of data storage include:

1. Magnetic Storage: Magnetic storage is one of the oldest and most widely used methods of data storage. It uses magnetism to record data on magnetic media, such as hard disk drives (HDDs) and magnetic tapes. Data is stored as patterns of magnetized particles on the medium, allowing for fast access and high capacity. Magnetic storage is commonly used in personal computers, servers, and data centers for long-term data retention and quick retrieval.
2. Solid-State Storage: Solid-state storage, also known as flash memory, has gained popularity due to its speed, durability, and low power consumption. It uses electronic circuits to store data in non-volatile memory cells. Solid-state drives (SSDs) are common in laptops, smartphones, and other portable devices, as well as in high-performance computing environments, offering faster data access times and reliability compared to traditional hard drives.
3. Optical Storage: Optical storage relies on lasers to read and write data on optical discs, such as CDs, DVDs, and Blu-ray discs. These discs have a reflective surface with microscopic pits and lands representing binary data. Optical storage is often used for distributing software, movies, music, and archival purposes.
4. Cloud Storage: Cloud storage involves storing data on remote servers accessible via the internet. It allows users to access their data from any connected device, offering scalability, data redundancy, and backup services. Cloud storage is widely used for data backup, file sharing, collaboration, and data synchronization.
5. Tape Storage: Although less common in personal computing, tape storage is still used in large-scale data backup and archiving. Tape storage offers high capacity and cost-effectiveness for long-term data retention.

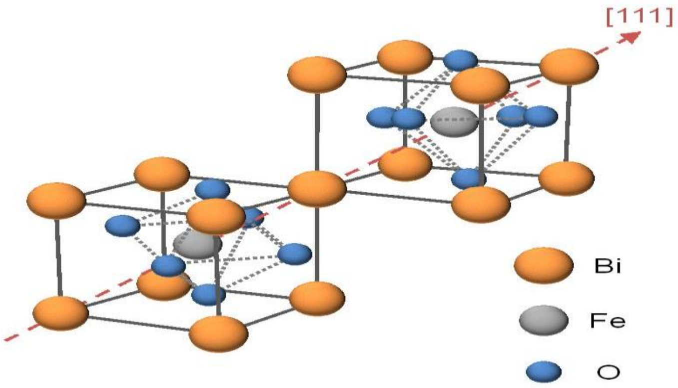
Data storage plays a critical role in our digital world, enabling the preservation and accessibility of vast amounts of information. As technology continues to advance, data storage solutions are expected to become more efficient, scalable, and secure, meeting the ever-growing demands of data-intensive applications and industries.

Figure 9: Application of Bismuth ferrite-based Nanomaterial for magnetic storage[65].

Physical Properties of BFO

In this book chapter our main focuses on piezoelectric, magnetic, magnetoelectric coupling, and photovoltaic properties of BFO-based nanomaterials.

1. **Crystal Structure**: Bismuth Ferrite crystallizes in a rhombohedral crystal structure at room temperature. It undergoes a phase transition at around 830°C, changing to a cubic structure at higher temperatures [61].



The spontaneous polarization of BFO arises from the relative shift of Bi^{3+} within the oxygen octahedron, forming an electric dipole moment. However, the presence of oxygen vacancies and fluctuations in the valence of Fe during BFO preparation led to increased leakage current and hindered saturation of ferroelectric hysteresis at room temperature [62]. In the 1970s, BFO ceramic bulk exhibited a polarization of 6.1 μC cm^{-2} at 77 K. In 2003, a breakthrough occurred with a fully saturated polarization of 55 μC cm−2 in a BFO thin film [63]. Efforts to reduce leakage currents through ion substitution and solid solutions with ABO_3-type perovskites have been undertaken to enhance ferroelectric and piezoelectric performance [64].

Numerous studies have focused on ion substitution with lanthanide rare earth elements in BFO-based nanomaterials. Figure 3d demonstrates the remarkable variation in the piezoelectric coefficient (d33) with different rare earth dopants (Dy^{3+} or Sm^{3+}) as a function of composition. At approximately 14% Sm composition, a significant increase in the dielectric constant, reaching 400, was observed, along with a concurrent rise in d33 to over 100 pm/V. These enhancements in dielectric constant and piezoelectric coefficient are attributed to the formation of distinct structures: Sm compositions below 14% exhibit a rhombohedral phase, whereas at 20% Sm, an orthorhombic structure emerges. Simultaneously, the ferroelectric hysteresis loops of Sm-doped BFO undergo a drastic change, transitioning from a standard shape at Sm compositions below 13%

to a double hysteresis pattern at 14% and higher. This behavior has been observed not only with Sm but also with other rare earth dopants (Dy, Gd, La)-doped BFO, suggesting its universality. The key factor influencing hysteresis curves, dielectric constant, and d33 is the average radius of the rare earth ionic species, indicating that phase structure changes can be controlled by tuning the average A-site ionic radius. These findings pave the way for tailoring BFO-based nanomaterials with improved properties for various applications, including energy harvesting, sensing, and data storage.

2. **Ferroelectricity**: Bismuth Ferrite is known for its strong ferroelectric properties, which means it can exhibit a spontaneous electric polarization that can be reversed by an external electric field [57]. Bismuth Ferrite (BiFeO3 or BFO) is a fascinating multiferroic material that exhibits strong ferroelectricity, making it a subject of significant interest in the field of condensed matter physics and materials science. Ferroelectricity is the property of certain materials to possess a spontaneous electric polarization that can be reversed or switched by the application of an external electric field [58].

In Bismuth Ferrite, the ferroelectric behaviour arises from the displacement of charged atoms (ions) within its crystal structure. The asymmetric arrangement of atoms in the unit cell leads to the development of a permanent electric dipole moment, resulting in spontaneous polarization. The switching of polarization occurs through domain wall motion, where regions with different polarization orientations (domains) reorient in response to external stimuli [60]. The remarkable ferroelectric properties of Bismuth Ferrite are of particular interest for various technological applications. It has been explored for use in non-volatile memory devices, such as Fe - RAM (Ferroelectric

Random Access Memory), due to its ability to retain information even when the power is turned off. Additionally, Bismuth Ferrite's piezoelectric characteristics have potential applications in sensors and actuators [59]. The study of BFO and other ferroelectric materials continues to advance, driven by the desire to develop novel electronic and spintronic devices that harness the unique properties of these materials. Researchers aim to understand the underlying physics of ferroelectricity in Bismuth Ferrite and explore ways to control and optimize its properties for practical applications in modern technology.

3. **Magnetic Properties**: Bismuth Ferrite is also ferromagnetic at room temperature, meaning it has a permanent magnetic moment. This coexistence of ferroelectric and ferromagnetic properties makes it a promising material for applications in spintronics and magnetoelectric devices [56].
4. Curie Temperature: The Curie temperature, Tc, is the temperature at which a material loses its ferroelectric and ferromagnetic properties. For Bismuth Ferrite, the Curie temperature is relatively high at around 830°C.
5. Dielectric Constant: Bismuth Ferrite has a high dielectric constant, which means it is an excellent insulator and can store electric charges effectively.
6. Piezoelectricity: Bismuth Ferrite is also piezoelectric, meaning it can generate an electric charge when subjected to mechanical stress.
7. Optical Properties: Bismuth Ferrite exhibits interesting optical properties, making it useful for applications in optoelectronics and photonics.
8. Chemical Stability: Bismuth Ferrite is chemically stable, which is essential for its practical applications.

It's worth noting that scientific research and material properties might have evolved since my last update. For the most current and specific information, I recommend consulting recent research papers or reliable sources in the field of materials science.

Summary and Outlook

In summary, Bismuth ferrite (BFO) emerges as a highly promising and versatile multiferroic nanomaterial, boasting unique properties such as substantial remnant polarization, room-temperature magnetoelectric coupling, and a relatively narrow bandgap. These characteristics make BFO an ideal platform for exploring novel techniques and functionalities. This review article highlights the significant achievements in investigating the structures, properties, and applications of BFO-based nanomaterials.

Researchers have proposed various strategies to modify the ferroelectric and magnetic performances of BFO, including ion substitution, proper substrate selection, and the construction of morphotropic phase boundaries, leading to improved properties. Additionally, size effects in BFO nanostructures have attracted great interest and have been studied extensively to enhance the material's behavior.

To unlock BFO's full potential, researchers face numerous challenges.

1. Firstly, there is a strong drive to further enhance the ferroelectric and magnetoelectric performances of BFO. While the material already exhibits high polarizations, the goal is to attain even higher ferroelectric polarization and piezoelectric activity comparable to piezoelectric ceramic transducers. Moreover, researchers seek to achieve a substantial magnetoelectric response at room temperature, which is crucial for the development of advanced multiferroic devices.
2. Secondly, dynamics parameters play a crucial role in the performance of BFO-based devices. Stabilizing the responding dynamics and achieving satisfactory switching

speeds are essential for devices designed based on ferroelectric or ferromagnetic switching. Currently, the reported switching speed and endurance still fall short of meeting the requirements for universal memory applications, indicating that there is still significant progress to be made in applying BFO-based nanomaterials to memory technologies.

3. Thirdly, the physical mechanisms underlying the photovoltaic effect and photocatalytic behavior in BFO nanomaterials remain elusive. Further research is needed to understand these mechanisms fully. Gaining insight into these physical processes will be instrumental in extending the scope of BFO photocatalysts and photovoltaic devices, allowing them to find applications in diverse fields.
4. Fourthly, although some nanomaterials systems have demonstrated coupling properties similar to BFO, the majority of such systems have yet to be developed and explored. Identifying and investigating additional nanomaterials systems with coupling properties is essential for designing innovative devices and advancing the field.

In conclusion, this book chapter aims to provide an updated overview of the existing challenges and opportunities in BFO nanomaterial research, inspiring and encouraging researchers to continue pushing the boundaries of BFO's capabilities. As the scientific community works to overcome these challenges, the development of BFO nanomaterials holds great promise for revolutionizing various applications, from nonvolatile memories and piezoelectric sensors to photodetectors and beyond. Through continued research and collaboration, Bismuth ferrite nanomaterials have the potential to bring about transformative advancements in nanotechnology and contribute significantly to the future of multifunctional and efficient electronic devices.

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